MANAGEMENT AND SIMULATION OF AGRONOMIC PRACTICES FOR PURSUING HIGH MAIZE YIELDS IN GEORGIA

by

ANNA ORFANOU

(Under the Direction of Wesley M. Porter)

ABSTRACT

A three-year study (2016-2018) was conducted to evaluate the effects of high fertility management strategies on maize in the southeastern Coastal Plain of Georgia, USA. UGA Extension Service and Georgia Maize Growers recommended the C_E (yield goal: 22 Mg ha^{-1}) and C_G (yield goal: 28 Mg ha^{-1}) high fertilization treatments, respectively. The tillage changed from conventional the first year to conservation the following two years. During the season hourly soil water tension (SWT) data was collected in addition to tissue data at several vegetative and reproductive stages for avoiding water and nutrient stresses. Additionally, soil, phenology, and meteorological data were collected. No statistical differences were observed between the treatments, which shows increased fertilizer rates did not result in higher yields. The yield results were lower than the expected due to low soil pH and CEC. The 2016 yields were higher than the 2017 and 2018 due to lower minimum temperatures and higher solar radiation. The data collected throughout the field study were used in DSSAT CERES-Maize model for simulating the growth and development of maize. The 2018 observed data of leaf number per stem, leaf weight, vegetative N concentration, and yield were used for calibrating the CERES-Maize cultivar coefficients P1, P2, P5, G2, G3 and PHINT, and the 2016 and 2017 datasets were used for the model's evaluation. The model was successfully calibrated with high correlation values and d-stat (>0.8). The calibrated model was used for evaluating yields under different management scenarios regarding planting date and depth, row spacing, plant density, N fertilizer rates, number and timing of side-dress N applications, and irrigation method. The model showed that the optimum planting date varied from year to year due to the different meteorological conditions; scenarios of 4-6 cm planting depths were ideal for increasing yields; the narrower the row spacing the higher the yield; a plant density of 120K plants ha^{-1} resulted in higher yields; the higher the fertilizer rate the higher the yield but the lower the efficiency; higher yields were predicted with the sensor-based irrigation method compared to the UGA Extension Checkbook and rainfed.

INDEX WORDS: maize, high yields, high fertilization rates, DSSAT CERES-Maize, simulation modeling, agronomic management scenarios

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Introduction

According to the United States Department of Agriculture – National Agricultural Statistics Service (USDA-NASS, 2018), the world's most highly produced crop is maize (Zea mays) with almost 370 million Mg produced in the United States of America in 2018. In addition to that, the maize production in the USA is the largest in the world (USDA, 2018). One of the reasons maize production is being increased is due to the high interest in biofuels, especially in maize-based ethanol (Vories et al., 2009). Maize is one of the most important crops in the USA, which makes its management a top priority. One of the most significant issues for maize production is to find ways for maximizing yield while maintaining agricultural sustainability (Johnston et al., 2015). Studies have shown that the most important factors for increasing maize yield and nitrogen use efficiency (NUE) are the population density, the amount of nitrogen (N) fertilizer applied and genetic improvement (Lee and Tollenaar, 2007; Tollenaar and Lee, 2002). Maize yield can be increased by having an optimum level of plant density, which is related to water availability (Karasahin, 2015).

Maize physiology

The maize plant develops during vegetative (VE to VT) and reproductive growth stages (R1 to R6). VE occurs when maize plants emerge and in ideal heat and moisture conditions can happen within 5 days after planting (DAP), but in practice at least 2 weeks after are common. From VE each vegetative stage is determined by the number of visible collars, i.e. V1, V2, V3,

…., Vn until the VT stage, when the tassel is completely visible, and the plant has achieved its full height. Reproductive growth stages begin at silking (R1) and finish when the kernel has reached its maximum dry weight (R6). Table 1.1 shows the growing degree days (GDD) that are required for each maize growth stage to occur (PIONEER, 2016a, b).

Maize is sensitive to temperatures below 10 °C and above 30 °C as there is a decrease in yield as maize accumulates growing days below and above this threshold (Lobell et al., 2011; Schlenker and Roberts, 2009; Siebers et al., 2017). During reproductive stages, maize is more sensitive to temperature in comparison to vegetative stages (Barnabás et al., 2008b; Hatfield et al., 2011) and more specifically during silking and tasseling (Sánchez et al., 2014).

Table 1.1 Maize growth stages and required growing degree units characteristics (PIONEER, 2016a, b).

	Corn Growth Stage	**GDUs Required**	**Characteristics**
Vegetative stages	VE	100	Emergence
	V3	325	3 visible collars
	V6	550	6 visible collars
	V9	730	9 visible collars
	V12	910	12 visible collars
	V15	1045	15 visible collars
	V18	1180	18 visible collars
	VT	1260 (depends on maturity, may have <18 collars)	Visible tassel
Reproductive stages	R1	Depends on maturity	Visible silk
	R2	Depends on maturity	Blister (10-14 days after silking)
	R3	Depends on maturity	Milk (18-22 days after silking)
	R4	Depends on maturity	Dough (24-28 days after silking)
	R5	Depends on maturity	Kernels are dented (35-42 days after silking)
	R6	Depends on maturity	Kernels at maximum dry weight (55-65 days after silking)

Agronomic management practices

Planting

The planting period of maize in Georgia is between late February through mid-May and the harvesting period is between mid-June through mid-September (Lee, 2019; Martinez and Jones, 2011; Wright et al., 2004). Early planted maize usually performs better in terms of yield in comparison with late planted maize due to ideal temperatures during pollination and lower potential for insect and disease damage (Lee, 2019; Martinez and Jones, 2011; Wright et al., 2004). According to Kucharik (2008), early planting contributed to 19%-53% yield increases in Nebraska, South Dakota, Minnesota, Iowa, Wisconsin, and Michigan. According to Long et al. (2017), there is a high correlation between planting date and latitude, i.e. there is a specific planting window for maximizing maize yields according to the latitude. More specifically, the planting window for the 30-35^{o}N, where Georgia is also located, was 89-106 day of the year (DOY), 107-118 DOY for the 35-40^{o}N, less than 119 DOY for 40-45^{o}N, and less than 129 DOY for 45-50^{o}N.

Farmers favor planting maize in high plant density for pursuing high yields (Tokatlidis and Koutroubas, 2004) even if there is possibility for interplant competition, particularly for light, water, and nutrients (Tollenaar et al., 2006; Tollenaar and Wu, 1999), which affects maize growth (Antonietta et al., 2014). In a study conducted in the Mississippi Valley, plant densities of approximately 72K, 82K, 93K and 103K plants ha^{-1} produced similar yield results in one research site, while the 72K plants ha^{-1} resulted in higher yields compared to the other plant densities at the second site (Bruns and Abbas, 2005). In a research study conducted in the northern US corn belt, the results showed that hybrids adapted to this area may have greater yields if they are planted at greater plant densities than commonly used, compared to narrower row spacing than 0.76 m (Westgate et al., 1997). According to Farnham (2001), there is a strong interaction between row spacing and hybrid, since the results of their study showed that certain hybrids performed better at prescribed row spacings.

Tillage

Conservation tillage practices have the potential for improving root penetration, minimizing erosion, enhancing water infiltration and increasing overall yield (Box and Langdale, 1984). Until recently, conventional tillage was the common practice in many fields to control the density of weeds mechanically. Conventional tillage usually involves turning the whole of the topsoil. By applying conventional tillage, it is possible to accelerate the organic matter break-down due to soil inversion and thereby soil aeration is increased.

According to a study conducted in the US southeastern coastal plain, greater maize yields were produced with conventional compared to conservation tillage under adequate water at low levels of N. In the same study, the yields were maximized regardless of the tillage when the N rate was 200 kg ha^{-1}, while the conservation tillage resulted in significantly higher yields under drought conditions (Campbell et al., 1984). The comparison of conservation and conventional tillage in a long-term study showed that conservation tillage produced maize yields equal or greater than conventional tillage on slopping, well-drained and low organic matter soils. Conventional tillage though produced greater yields on poorly drained soils, high inorganic matter that were cropped to continuous maize (Kladivko et al., 1986). According to DeFelice et al. (2006), no-till had greater yields in the south and west regions of the US compared to the conventional tillage, while similar yields were produced in the central US and conventional tillage produced greater yields in the northern US and Canada. Furthermore, when there was maize soybean rotation in no-till systems, yields were greater than continuous cropping.

Cover crop

Cover crops grown between fall and planting of maize in the spring could be beneficial for soil and water quality by increasing soil organic matter, increasing soil structural quality, recycling nutrients, minimizing N and phosphorous (P) losses (Basche et al., 2016; Kaspar et al., 2007; Kaspar et al., 2012; Moore et al., 2014) and suppressing weeds (Teasdale et al., 2007). Different kinds of plant species can be used as cover crops depending on crop rotation, local climate conditions, period of the year that it needs to be planted and its potential growth. In the case of maize – soybean rotation, cover crops such as oat (Avena sativa L.), winter wheat (Triticum aestivum L.) and winter rye (Secale cereal L.) are often planted (Singer et al., 2007; Snapp et al., 2005).

Irrigation

According to (FAO, 2002), globally the highest amount of fresh water (70%) is used in agriculture for irrigation. Watering crops is a very important factor for increasing yields. However, the amount of water resources which can be used for irrigation is limited in many parts of the world (Gencoglan and Yazar, 1999). The main irrigation issue that needs to be addressed is finding ways to increase agricultural production while using less water, making irrigation efficiency crucial (Simsek et al., 2011).

Maize is vulnerable to water stress during the tasseling period, which occurs between May and July (Denmead and Shaw, 1960; Martinez and Jones, 2011; Otegui et al., 1995). Water stress can influence maize developmental and physiological processes, having as a result reduced biomass and consequently yield due to lower number of kernels per ear or kernel weight (Payero et al., 2009; Traore et al., 2000). According to Wright et al. (2004), maize requires 0.32 in of water per day from tasseling to grain filling. Silking, pollination, and early grain filling are sensitive to water for maize (Nielsen et al., 1996). Better maize yield results and other aspects of maize production, such as lower levels of maize earworm, could be achieved by timely irrigation (Smith and Riley, 1992).

Proper irrigation can assist crops in achieving maximum yield potential by reducing the stress of dry conditions. According to Wagger and Cassel (1993), water is the main limiting factor for crop production in the southeastern US. Their results showed that a full irrigation approach would result in greater yields compared to limited irrigation or dryland. It is highly suggested that one follows a scientific method of irrigation scheduling for maize production. In Georgia, methods such as the UGA checkbook method, developed from a historical average evapotranspiration (ET), or soil moisture sensors are valid irrigation scheduling methods. In the southern US, maize is primarily surface or center pivot irrigated (Vories et al., 2009). Grassini et al. (2011b) showed that 41% and 20% less irrigation was applied with pivot irrigation and conservation tillage compared to surface irrigation and conventional tillage under a maize-soybean rotation, indicating that pivot irrigation and conservation tillage has higher irrigation water use efficiency (IWUE).

Nutrition

Proper fertilization is a crucial factor for achieving high maize yield. N is the most important element for increasing maize productivity (Kara, 2006). Insufficient amounts of N could result in reductions of dry matter allocation and reproductive structures, which negatively influence maize yield (Ding et al., 2005; Monneveux et al., 2005; O'Neill et al., 2004; Seebauer et al., 2000). On the contrary, higher maize yield can be obtained when sufficient N is available thus allowing extended periods of post silking dry matter and N accumulation (Moll et al., 1994). N deficiency in maize can be identified through reductions in leaf area, leaf chlorophyll status and vegetative biomass (Echarte et al., 2008; Monneveux et al., 2005; Paponov and Engels, 2003). NUE in maize is the amount of grain produced per unit of applied N fertilizer. NUE provides a quantitative measure of the effectiveness of maize plants to absorb and convert available N into yield. At lower plant densities, maize reaches maturity without using all of the available N in the soil, while in higher densities the available N in the soil is decreased due to plant competition, as a result the NUE and consequently the maize yield per plant tend to decrease (Tollenaar et al., 2006). According to Grassini et al. (2011a), irrigated maize can achieve high levels of NUE.

Plants need phosphorus (P) for their growth development, especially during their early stages of their cycle to store and transfer energy. Moreover, phosphorus concentration is important for improving shoot and root growth and promoting early maturity. Low phosphorus level in the soil can have negative effects in the plants, especially under stressful conditions. Potassium (K) is also involved in the maize growth and development. It is associated with the movement of water, nutrients, and carbohydrates within the plants. Low concentration of K can result in difficulties regarding absorbing water and N from the soil. In a study that lasted five years, it was shown that N, P, K fertilizers increased yields more under irrigated than dryland conditions because the nutrients were activated and used by the plants (Videnović et al., 1986).

Simulation models

Simulation models can be useful tools to aid in the decision-making process about projecting changes in crop production. A simulation model can consider parameters such as planting dates, crop requirements, soil, and climate conditions to improve crop management. Decision support systems through simulation models have been used for optimizing irrigation practices, conserving rainwater, improving soil management, adjusting plant densities etc.

(Anapalli et al., 2005; Anapalli et al., 2004; Debaeke, 2004; Sivakumar and Glinni, 2002). Estimation of crop yield can be simulated through models for a growing season by using remotely sensed data.

The Decision Support System for Agrotechnology Transfer (DSSAT) models have been often used to characterize, develop, and assess field crop production practices. DSSAT is supported by data base management programs for soil, weather, and crop management and experimental data, and by utilities and application programs. It has been in use for more than 20 years by researchers. Scientists have used DSSAT for simulating various applications, such as irrigation management (Jones et al., 2003; Panda et al., 2004), precision agriculture and yield variability (Thorp et al., 2008). DSSAT CERES-Maize model is used for simulating maize development. Saseendran et al. (2008) calibrated and validated the CERES – maize model to assess irrigation scenarios that have potential to optimize water use efficiency during the crop growth period. In another study, DSSAT CERES-Maize was used to evaluate management practices under Mediterranean conditions and the results showed that adjusted irrigation could reduce the water applied by 31%, and the nitrate (NO_3-N) leaching by 97% without a significant reduction in yield (Malik et al., 2019). Chisanga et al. (2015) used the generalized likelihood uncertainty estimation (GLUE) program of DSSAT CERES-Maize to estimate the genetic coefficients. Their results showed that the model can be used successfully to determine planting dates, yield, and N rates.

Project description

The main focus of this three-year study was to maximize yields by applying high rates of N, P, and K fertilizers, irrigating when it was necessary based on soil moisture sensors installed in the field, and improving management practices across the years. Soil, plant and meteorological data were collected during the study to make decisions about the management practices, ensure that the plants were not under stresses, and be used for setting up, calibrating and evaluating the DSSAT CERES-Maize model. The calibrated model was used for simulating the maize production and evaluating yields under several management scenarios regarding planting date and depth, row spacing, plant density, N fertilizer rates, number and timing of side-dress N applications, and irrigation method.

Goals and objectives

The main objective of this project was to identify the limitations in agronomic management practices for pursuing high maize yields. This objective was accomplished by completing the following sub-objectives:

a. Measure the agronomic response of maize to high yield management practices.
b. Use of DSSAT CERES-Maize model to simulate maize growth and development and estimate yields.
c. Use of DSSAT CERES-Maize model to evaluate management scenarios that could result in high maize yields.

CHAPTER 2

EFFECTS OF INTENSIVE NUTRIENT MANAGEMENT PRACTICES ON MAIZE YIELD[1]

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[1] Orfanou, A., D. Pavlou, G. Vellidis, K.J. Boote, C.J. Bryant, M.L. Cabrera, R.L. Noland, and W.M. Porter. To be submitted to *Field Crops Research*.

Abstract

A three-year study, from 2016 to 2018, was conducted to evaluate the effect of high fertility management strategies on maize (Zea Mays) in the southeastern Coastal Plain of Georgia, USA. The study took place in a 1.44 ha field with Tifton loamy sand soil type, located in Tifton, GA. Two high fertilization treatments were included in the study based on the professional recommendations of UGA Extension Service (C_E) and Georgia Maize Growers (C_G) for achieving high yields of 22 Mg ha^{-1} and 28 Mg ha^{-1}, respectively. Conventional tillage was implemented during the first year of the project while conservation was used the following two years with the effort focused on increasing yield. Soil water tension (SWT) data was collected throughout the growing seasons for irrigation purposes to avoid water stresses, and tissue samples were collected at several vegetative and reproductive stages to prevent nutrient stresses. The yield goals were not achieved and the yield results ranged from an average of 13 Mg ha^{-1} to 16 Mg ha^{-1} depending on the year, which was the outcome of the soil conditions, i.e. low pH and CEC. The 2016 growing season had the highest yield results compared to 2017 and 2018 due to favorable weather conditions, i.e. lower minimum temperatures, and higher solar radiation. The yield results were not statistically significant different between the C_E and C_G treatments, which shows that the increased fertilizer rates did not result in greater yields.

Introduction

The agricultural sector is motivated to increasing yields of agronomic crops for supplying the needs for food and biofuels of the growing population (Vories et al., 2009). One of the world’s most highly produced crops is maize (Zea mays), which produced 41% of the total world grain production during 2017 (USDA, 2018). Three countries dominate maize production, USA, China and Brazil, producing nearly to 563 million Mg per year while the total production is close to 717 million Mg per year (Ranum et al., 2014). Among those countries, the USA is considered to be the world's largest maize producer, with 35% of the world's maize production in 2017 (USDA, 2018).

Agronomic management practices for increasing yields

Important improvements in maize productivity have resulted in significant yield increases in the USA from 1870 to today, making maize the most significant cereal in the world (Duvick, 2005b; USDA-NASS, 2018). Before 1940, the US average maize yield was between 1.2 Mg ha^{-1} and 1.9 Mg ha^{-1} while by 2017 the yield had increased to 11.1 Mg ha^{-1} (USDA-NASS, 2018). The adoption of improved hybrids that were better at capturing soil nutrients and being more resistant to lodging, biotic (pests, weeds, deceases) and abiotic (adverse weather) stresses (Duvick, 2005b), and improved management practices were important factors for increasing maize yield over the years. These management practices include the use of fertilizers, irrigation, tillage methods, crop rotation, increased plant density, and weed and pest control.

Fertilizers are applied to the soil to ensure that nutrients are available to the plants during the growing season. Thus, proper fertilization is a crucial factor for achieving high grain yields. One of the most important nutrients for increasing maize yield is nitrogen (N) (Amanullah et al., 2016). Extended periods of post silking dry matter and N accumulation, which may result in higher yields, can be achieved when sufficient N is available (Moll et al., 1994), while insufficient amounts of N can result in reductions of dry matter accumulation and reproductive structures, which negatively influence maize yield (Ding et al., 2005; Monneveux et al., 2005; O'Neill et al., 2004; Seebauer et al., 2000). Plant density can play an important role at the availability of N in the soil due to plant competition. At lower plant densities, maize reaches maturity without using all of the available N in the soil (Tollenaar et al., 2006). An 18-year study conducted by Schlegel and Havlin (2017), showed that optimum yields ranged from 9.8 Mg ha^{-1} to 16.3 Mg ha^{-1} in the same field. This indicates that optimum N rates are often variable even within a field. According to a metadata analysis of 213 site-years study conducted by Dhital and Raun (2016), N rates should be adjusted by year and location. N use efficiency (NUE) provides a quantitative measure of the effectiveness of maize plants to absorb and convert available N into yield. Based on a three-year study, NUE decreased with increasing N rate while narrow row spacing increased NUE up to 15% (Barbieri et al., 2008). A study conducted in Kansas showed that N recommendations can be reduced by an average of 40% by splitting the N fertilizer applications without affecting negatively maize yield results (Gehl et al., 2005).

Phosphorus (P) is applied to the soil to support crop growth and grain yield in the form of mineral fertilizer, and animal and urban manure. A five-year field experiment showed that maize yield was increased as the P rates increased. However, P fertilizer application did not have any impact when rainfall was below average, which influenced negatively crop growth (Ibrikci et al., 2005). According to Heckman and Kamprath (1992) the low reserves of potassium (K) in sandy Coastal Plain soils may not be sufficient for intensive maize production. Their three-year experiment showed that maize yield increased linearly with K rates up to 112 kg ha^{-1} when the initial exchangeable-K level was 0.21 cmol L^{-1}. Crop rotation has also been used by farmers to restore soil fertility (Anderson, 2005; Bullock, 1992). The results of Boring et al. (2018) showed that it is possible across the US to apply P and K fertilizers biennially in a maize-soybean rotation system without affecting yields negatively.

Proper irrigation can prevent soil water scarcity and drought and assist crops in achieving maximum yield potential by reducing the stress of dry conditions. Water stress can result in reduced biomass and consequently yield due to a lower number of kernels per ear or kernel weight (Payero et al., 2009; Traore et al., 2000). Maize is most vulnerable to water stress during the tasseling period (Denmead and Shaw, 1960; Martinez and Jones, 2011; Otegui et al., 1995). Maize requirements are as much as 7.87 mm of water per day at tasseling and can reach up to 8.64 mm at early dough stage in Georgia (Lee, 2019). Better maize yield results can be achieved by timely irrigation (Smith and Riley, 1992). For instance, in Minnesota, irrigated maize response was similar to midseason irrigation as it was to more frequent irrigations at 50% soil water depletion (Johnson et al., 1987). In Georgia, methods such as the UGA Extension maize checkbook, developed from a historical average evapotranspiration (ET), or soil moisture sensors are valid irrigation scheduling methods. In the southern USA, maize is primarily surface or center pivot irrigated (Vories et al., 2009).

Optimizing plant density, which is the total number of plants present in an area (plants ha^{-1}) may have favorable maize yield results (Karasahin, 2015; Lee and Tollenaar, 2007; Tollenaar and Lee, 2002). However, there should be caution when the number of plants per ha is decided because high plant densities affect interplant competition, particularly for light, water, and nutrients (Tollenaar et al., 2006; Tollenaar and Wu, 1999), which affects maize growth (Antonietta et al., 2014).

Tillage plays an important role in maize production and consequently on its final yield. Even if conventional tillage was the main practice in many fields until recently, conservation tillage has started gaining recognition as a practice that not only preserves water, but also aids in achieving acceptable maize yield results (Orfanou et al., 2019). In general, studies have shown that conservation tillage practices can lead to better root penetration, enhanced water infiltration, minimized erosion and overall yield (Box and Langdale, 1984). Furthermore, strip tillage and no-till can have favorable results in maize yield and water productivity (grain yield/ crop water use) and can be used especially in areas that are water limited (Lamm et al., 2009). Tillage can be beneficial to pest and weed control but can also be achieved with crop rotation and the use of pesticides. The results of a study which compared tillage systems and fertilizer placements showed that strip tillage with deep band can improve conditions for nutrient uptake which can lead to greater maize yields compared to no-till systems (Fernández and White, 2012).

Meteorological conditions during maize production

Besides the management practices followed during the maize growing season, meteorological conditions are also important for achieving successful yield results. The planting period of maize in Georgia is between late February through mid-May and the harvesting period is between mid-June through mid-September (Lee, 2019; Martinez and Jones, 2011; Wright et al., 2004). Early planted maize usually performs better in terms of yield in comparison with late planted maize due to ideal temperatures during pollination and lower potential for insect and disease damage (Lee, 2019; Martinez and Jones, 2011; Wright et al., 2004). Ideal soil temperatures, above 13 ^{o}C, can assist maize in germinating and emerging in seven days or less after planting. Otherwise, when the soil temperatures are below 10 ^{o}C, there is a risk of slow and uneven emergence. According to Nielsen (2014), 56-67 ^{o}C GDDs are required for maize to emerge, which means 5-7 days, but under cold conditions, it might take longer (Nielsen, 2014). Maize is sensitive to temperatures below 10^{o}C and above 30^{o}C as there is a decrease in yield as maize accumulates growing days below and above this threshold (Lobell et al., 2011; Schlenker and Roberts, 2009; Siebers et al., 2017). During reproductive stages, maize is more sensitive to temperature in comparison to vegetative stages (Barnabás et al., 2008a; Hatfield et al., 2011) and more specifically during silking and tasseling (Sánchez et al., 2014).

Goals and Objectives

The goal of this study was to evaluate the yield response of maize to high fertilization rates under typical field production conditions encountered by maize growers in the southeastern Coastal Plain of Georgia, USA.

Materials and methods

Field description

A three-year project began in 2016 and was carried through the 2018 production season for a total of three consecutive maize growing seasons, in the NESPAL field, which is located at the University of Georgia's Tifton Campus (31^{o}28'44.05" N, 83^{o}31'55.00" W) in Tifton, GA. The climate of Tifton-Vidalia Upland portion of the Gulf-Atlantic Coastal Plain is humid subtropical with 1208 mm average annual precipitation, 12.72 ^{o}C minimum and 25.17 ^{o}C maximum temperatures (University of Georgia Weather Network (UGAWN)). The maize growing season lasts from March to August in the southeastern Coastal Plain of Georgia, USA. These months are the warmest with the most precipitation of the year. The average temperatures range from 14.72 ^{o}C in March to 27.14 ^{o}C in July, the rainy days range from 7 days in April to 14 days in July, and the average total precipitation is 682 mm.

The field was 1.44 ha and consisted of six blocks of cultivated land shown with white borders in Figure 2.1. Three of the blocks were located at the west side (W1, W2 and W3) and the other three at the east side of the field (E1, E2 and E3). Block size ranged from 0.18 ha to 0.34 ha. Based on the size of each block, it was divided into either four or six plots so that each plot contained at least twelve 0.91 m wide rows. The two blocks at the northern part of the field, W1 and E1, contained twenty-four rows while the other four blocks contained thirty-six rows. Thus, W1 and E1 blocks were the only blocks separated into four plots. The 32 plots ranged in size from 121 m^2 to 526 m^2. The crop rows run from west to east. An alley was established on a north-south axis between the plots to allow for access and turning of field equipment.

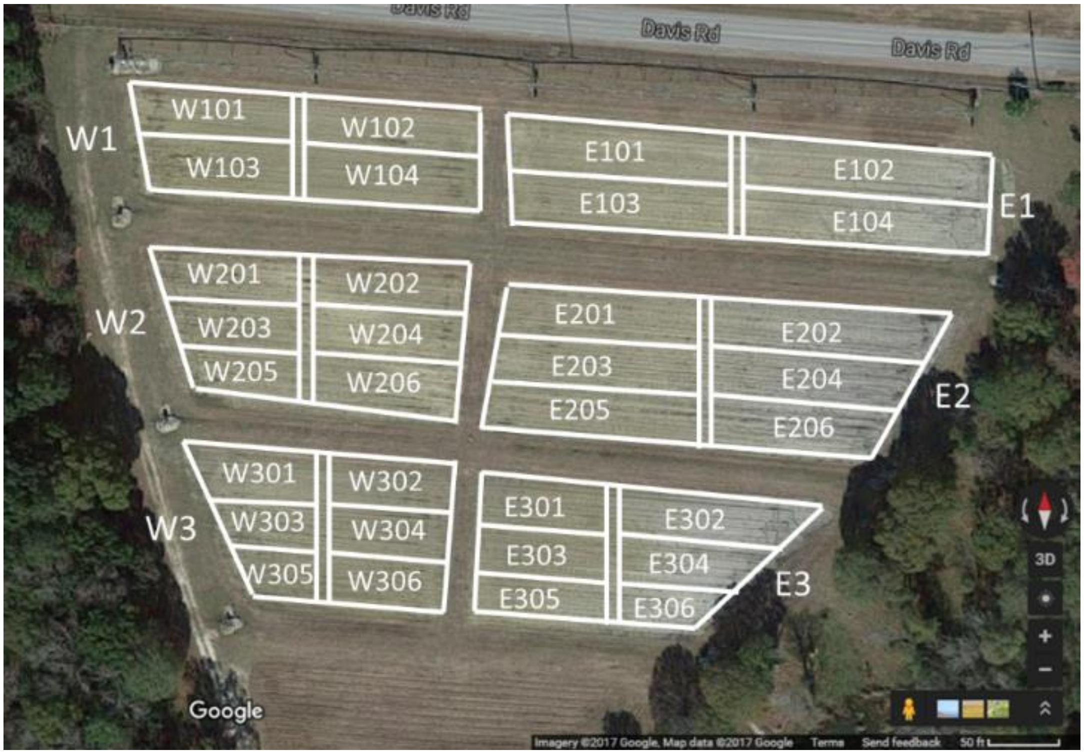


Figure 2.1 Graphical representation of the field, blocks, and plots.

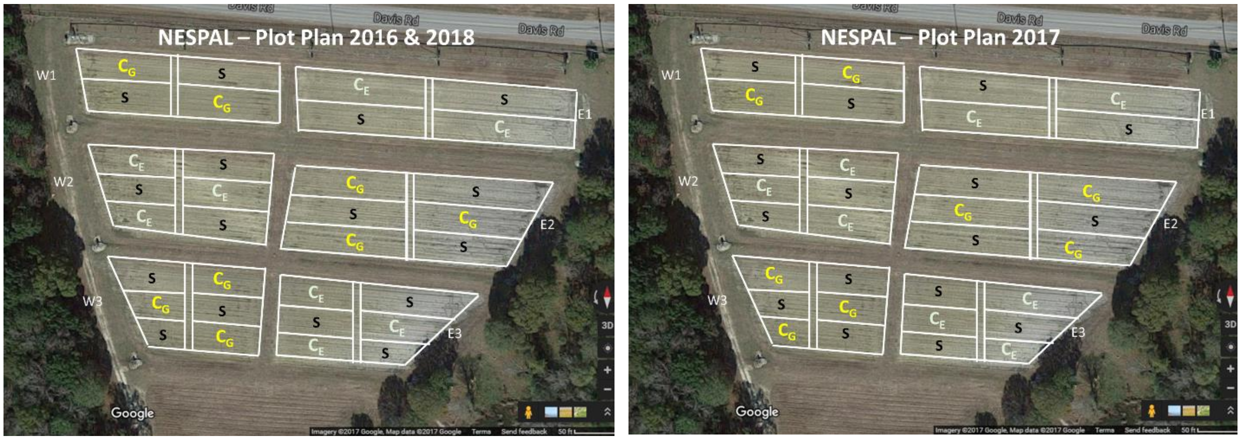
The soil series of most of the field area is Tifton loamy sand, which is characterized as deep and well drained by NRCS Soil Survey. Additionally, the soil of half of the area of the eastern blocks (E1, E2 and E3) is an Alapaha loamy sand, which is also deep but poorly drained. There is a visible color difference between the soil series as it can be seen in Figure 2.1 and Figure 2.2. Both soil series are low in natural fertility and organic matter and very strongly acid.

Experimental design

During each growing season, sixteen of thirty-two plots were planted with maize, variety P1794VYHR (Pioneer, Johnston, IA, USA), indicated with C_E and C_G in Figure 2.2. The C_E and C_G refer to the two fertilization treatments recommended by the UGA Extension Service and

Georgia Maize Growers, respectively. The C_E and C_G treatments had yield goals of 22 Mg ha^{-1} and 28 Mg ha^{-1}, respectively. The rates of each fertilization treatment are presented in Table 2.1. Three blocks were randomly assigned to the C_E (W2, E1 and E3) and C_G treatment (W1, W3 and E2). All the plots within each block were assigned to the block's treatment and each treatment had eight replications.

An annual rotation between maize and soybeans (Glycine max) was established. Half of the plots within a block were planted with soybeans and their location is indicated with S in Figure 2.2. The focus of the project was only on the maize plots. Thus, soybeans were planted only for a proper crop rotation throughout the three years of the project and they were not fertilized.



(a) (b)

Figure 2.2 Plot plans of NESPAL field indicating the location of soybeans (S) and maize (C_E and C_G fertilization treatments) plots during the (a) 2016 and 2018, and (b) 2017 growing seasons.

Table 2.1 Fertilizer rates and application dates for C_E and C_G treatments during the 2016, 2017 and 2018 growing seasons.

Year	**Type**	**Date**	**C_E**			**C_G**		
			N	**P_2O_5**	**K_2O**	**N**	**P_2O_5**	**K_2O**
			kg ha^{-1}					
2016	Preplant	15 Mar	110	67	191	110	200	370
	At planting	16 Mar	47	45	N/A	47	45	N/A
	Side-dress	8 Apr	100	N/A	N/A	110	N/A	N/A
	Side-dress	25 Apr	100	N/A	N/A	230	N/A	N/A
	Total		**357**	**112**	**191**	**497**	**245**	**370**
2017	Preplant	15 Mar	90	146	291	90	213	404
	At planting	21 Mar	48	44	N/A	48	44	N/A
	Side-dress	13 Apr	123	N/A	N/A	123	N/A	N/A
	Side-dress	21 Apr	123	N/A	N/A	63	N/A	N/A
	Side-dress	2 May	N/A	N/A	N/A	63	N/A	N/A
	Side-dress	12 May	N/A	N/A	N/A	63	N/A	N/A
	Side-dress	26 May	N/A	N/A	N/A	63	N/A	N/A
	Side-dress	2 Jun	N/A	N/A	N/A	27	N/A	N/A
	Total		**383**	**191**	**291**	**540**	**257**	**404**
2018	Preplant	22 Mar	30	101	247	64	202	392
	At planting	28 Mar	48	44	N/A	48	44	N/A
	Side-dress	24 Apr	112	N/A	N/A	112	N/A	N/A
	Side-dress	8 May	56	N/A	N/A	56	N/A	N/A
	Side-dress	23 May	56	N/A	N/A	112	N/A	N/A
	Side-dress	5 Jun	N/A	N/A	N/A	112	N/A	N/A
	Total		**302**	**145**	**247**	**504**	**246**	**392**

Management practices

Planting maize

The planting date depended on the soil temperature and it took place on the 16th of March 2016, 21st of March 2017, and 28th of March 2018. The seeding rates were at 79000 seeds ha^{-1} for the C_E plots throughout the study, and 79000 seeds ha^{-1} for the C_G in the 2016 and 2017 growing seasons and increased to 97850 seeds ha^{-1} in the 2018 in the attempt to achieve higher yields. The seeds were planted at 0.05 m depth and the planting method was bedded.

Tillage and cover crop

Cover crop was not planted the first year of the project because instrumentation was being installed in the field prior to the planting of maize. For that reason, conventional tillage was utilized in the first year of the project. The following two years, cover crops, i.e. rye in 2017 and wheat in 2018, were planted. The cover crop was planted in October each year with a seed drill into the maize residue. The cover crop was terminated using herbicides in late February and conservation (strip) tillage was implemented before planting maize in spring.

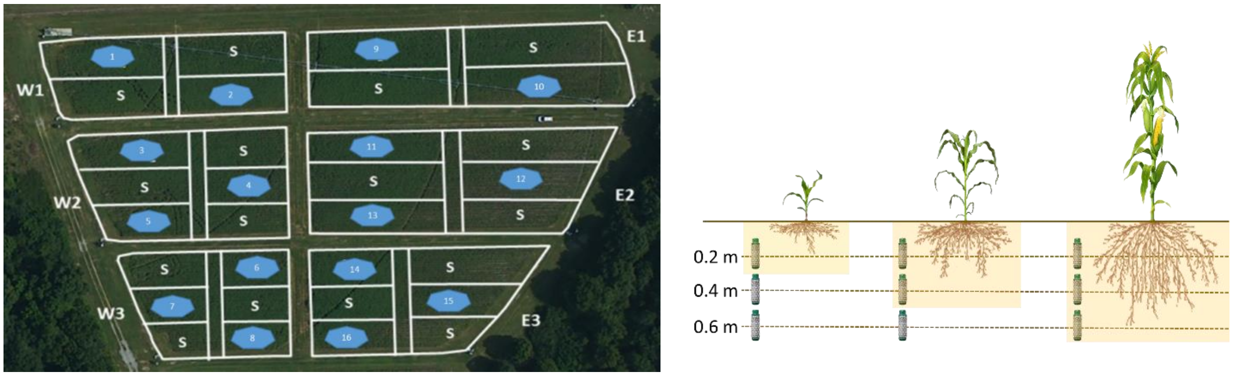
Fertilizer applications for maize

Granular fertilizer was applied to the maize plots prior to planting. In the 2016 growing season, the preplant fertilizer was applied in the form of 46-0-0 Urea-Bulk, 10-50-0 monoammonium phosphate (MAP), and 0-0-60 muriate of potash (MOP). In the 2017 growing season, the preplant fertilizer was applied in the form of 12-40-0 10S MES10, 0-0-60 MOP and ammonia nitrate (bulk). In the 2018 growing season, the preplant fertilizer was applied in the form of 12-40-0 10S MES10 and 0-0-60 MOP.

Liquid fertilizer in the form of 10-34-0 ammonium polyphosphate solution was dribbled on the soil surface at planting in each growing season. The remaining amount of N fertilizer was side-dressed in a liquid form of ammonium nitrate (NH_4NO_3) into multiple applications. The side-dress applications were also dribbled on the soil surface. The fertilizer rates are shown in detail in Table 2.1. No fertilizer was applied to the soybean plots to avoid fertilizer carryover effects on the maize plots.

Irrigation scheduling

Irrigation was scheduled based on soil moisture data from the University of Georgia Smart Sensor Array (UGA SSA). Three Watermark® sensors, constituting a node, were installed at depths of 0.2 m, 0.4 m and 0.6 m in each maize plot, comprising sixteen nodes in total (Figure 2.3). Soil Water Tension (SWT) data from each sensor was recorded hourly. The readings collected at 7:00 AM were applied in Eq. 2.1 for making irrigation decisions. A weighted percentage was assigned to each sensor (α, β and γ) based on the plants' root growth, which was correlated to growing degree days (GDDs) based on previous research (Kranz et al., 2008; Lee, 2007). These percentages were dynamic, meaning that they were changing through time, and were based on the plants' development (Table 2.2). The graph in Figure 2.3(b) shows a visual representation (yellow boxes) of the significance of the soil moisture sensors according to the plant's root development. According to Liang et al. (2016), the field capacity of NESPAL field, which has Tifton loamy sand, ranged from 0.18 cm^3 cm^{-3} to 0.23 cm^3 cm^{-3} and the SWT at field capacity ranged from 6 kPa to 15 kPa. When the SWT weighted average (Eq. 2.1) of the three sensors approached 30 kPa to 35 kPa irrigation was triggered and the field was irrigated with a center pivot (Orfanou et al., 2019).



(a) (b)

Figure 2.3. (a) Location of each node of three soil moisture sensors shown with blue polygons for the 2016 and 2018 plot plans, and (b) underground location of the soil moisture sensors and their significance based on the plants' and roots' development.

$$SWT_{Weighted\ Average} = \alpha * SWT_{0.2\ m} + \beta * SWT_{0.4\ m} + \gamma * SWT_{0.6\ m} \qquad \text{Eq. 2.1}$$

Table 2.2 Weight of each soil moisture sensor based on the GDDs and phenological stage.

GDDs (ºC)	**Growing stage**	**α – 0.2 m (%)**	**β – 0.4 m (%)**	**γ – 0.61 m (%)**
0-354	VE-V4	80	20	0
355-724	V5-V8	60	30	10
725-878	V9-V11	50	30	20
879-1099	V12-VT	50	25	25
1100<	R1-black layer	40	30	30

Intensification of management

Management practices were adjusted throughout the study to address observed problems that could limit yield. Runoff was observed consistently during irrigation and rainfall events throughout the 2016 growing season (Pavlou et al., 2020a). To minimize runoff, the tillage was changed from conventional to conservation and cover crops were used. Additionally, the pivot's application rate was reduced from 71.12 mm h^{-1} in 2016 to 35.56 mm h^{-1} the following two years. Furthermore, the goal to achieve greater yields the following years led to increasing the seeding rate and splitting the total rate of N into multiple side-dress applications. The seeding rate of the C_G treatment was increased from 79000 seeds ha^{-1} to 97850 seeds ha^{-1} during the 2018 growing season and the fertilization applications were increased from two to six during 2017 and 2018 only for the C_G treatment. Lime was applied before the 2017 and 2018 growing seasons at the rates of 3.36 Mg ha^{-1} and 4.48 Mg ha^{-1}, respectively, with a pull type spreader to increase soil pH and consequently yields.

Data collection

Several of the twelve rows in each maize plot were assigned a specific role as shown in Figure 2.4. Rows 1, 2, 11 and 12 were designated as buffers. Row 4 was used for counting the emergence of maize plants and to be hand harvested at the end of the growing season to correlate emergence rate with the yield results. Therefore, a row close to the middle of the plot but not next to the yield rows was important so that it was ensured that yield rows would not be affected while counting or harvesting the emergence row. Soil moisture sensors were necessary for making irrigation decisions and they had to be installed as close to the yield rows as possible (row 5). Rows 6 and 7 were in the very middle of the plots and were used for collecting the yield data. Destructive tissue samples were collected from row 10 during 2016 growing season. However, when the number of destructive samples increased the following years, two more rows (3 and 9) were necessary for the purpose of the project. Those rows were chosen to be as far as possible from the yield rows to avoid favoring or causing problems to them.

Buffer	1
Buffer	2
Plant samples	3
Emergence	4
Soil moisture sensors	5
Yield	6
Yield	7
	8
Plant samples	9
Plant samples	10
Buffer	11
Buffer	12

Figure 2.4 Graphical representation of a maize plot in the NESPAL field.

Emergence data

Emergence data were collected to ensure that most of the plants emerged during the first week after planting and there was a good stand. Three plots from each treatment were chosen randomly for plant emergence counts, having six plots from the whole field in total during the

2016 and 2017 growing seasons. During the third year of the project, emergence data were collected from all the plots of the field. A 3 m length of a row was measured in the center of the fourth row and used for the counts which were performed every 12 hours, at 07:30 AM and 07:30 PM, until all plants emerged. Each plant was marked with a metallic tag indicating the date and time of its emergence. At the end of the growing season, each plant, from the area that emergence was monitored, was hand harvested and the yield was correlated to the date and time of its emergence.

Soil sampling

One intact soil core sample of 0.75 m depth was collected from each plot in February, before maize was planted, and in September, after the maize was harvested. The locations from which the soil cores were collected were distributed across the block to capture any variability that existed. Each core soil sample was split into five 0.15 m segments. Each segment was dried at 100 ^{o}C and their weight before and after drying was taken. The soil samples were analyzed with Mehlich 1 for OM, pH, P, K, Ca, Mg, Mn, Zn, S, Fe, Cu, B, CEC by a commercial laboratory (data is presented in APPENDIX A). The soil data was used for adding lime, phosphorus, potassium and micronutrients, and for evaluating the maize yield results.

Plant samples

During the 2016 growing season, seven plant samples were collected during the stages of V3, V4, V7, V12, VT, R3 and R4. During 2017 and 2018, the sampling events were increased to a total of 12 and 16 samples, respectively. In 2017, samples were collected during the stages of V3, V4, V6, V7, V10, V12, V16, VT, R1, R3, R4 and R6, while in 2018, at the stages of V3, V4, V5, V6, V7, V8, V10, V12, V14, VT, R1, R2, R3, R4, R5 and R6 (data is presented in APPENDIX B).

Tissue samples were collected throughout the growing seasons for guaranteeing that there were no nutrient deficiencies that could cause yield limitations. When the plants were at the early vegetative stage the whole plant was sampled to ensure enough plant material was collected. From V6 to VT the first fully developed leaf below the whorl was collected, while the leaf at the ear node was sampled once the plants reached the reproductive stages. All the samples were analyzed for N, P, K, Ca, Mg, S, Mn, Fe, B, Cu, and Zn by a commercial laboratory.

Weather, SWT and irrigation

Meteorological data were important for making decisions before the maize was planted as well as during the growing season. Soil temperature data were used for deciding the planting date, which should occur when the soil temperature is at or above 13 ^{o}C. Maximum and minimum air temperature data were used for estimating the GDDs, which were used for estimating the SWT weighted average (Eq. 2.1), based on which the irrigation was scheduled. Rainfall data were necessary for estimating the total amount of water received by the plants during the growing seasons and was correlated to the final yield. Solar radiation was another important factor that was used to explain yield results. The access to the Tifton, GA, weather station was done through the UGAWN, from which all the weather data were downloaded (www.georgiaweather.net).

Harvest and yield estimation

Maize was mechanically harvested from the middle two rows of each plot at physiological maturity with the University of Georgia Variety Trial Program’s plot-scale grain combine. The harvest occurred on the 19th of August 2016, 29th of August 2017 and 22nd of August 2018. The yield was estimated, in bu ac^{-1}, by using the following equations and it was converted to kg ha^{-1} by applying the Eq. 2.6.

$$Plot\ area = Plot\ width * Plot\ length \qquad \text{Eq. 2.2}$$

$$Harvested\ dry\ matter\ (lbs) = (100\% - Measured\ moisture\%) * Harvest\ weight\ (lbs) \qquad \text{Eq. 2.3}$$

$$Standard\left(\frac{lbs}{bu}\right) = (100\% - Standard\ moisture\%) * Standard\ bushel\ weight(lbs) \qquad \text{Eq. 2.4}$$

where,

Standard moisture is 15.5%

Standard bushel weight is 56 lbs/bu

$$Yield\left(\frac{bu}{ac}\right) = \frac{\dfrac{Harvested\ dry\ matter(lbs)}{Standard\ \left(\frac{lbs}{bu}\right)}}{Plot\ area\ (ac)} \qquad \text{Eq. 2.5}$$

$$Yield\left(\frac{kg}{ha}\right) = 62.77 * Yield\left(\frac{bu}{ac}\right) \qquad \text{Eq. 2.6}$$

Statistical analysis

A statistical analysis was performed with JMP® Pro 14.1.0 (JMP®, Pro 14.1.0, SAS Institute Inc., Cary, NC, 1989-2019) to determine significant differences on the response variables between the fertilization treatments during each year of the project separately and by combining the three years of the experiment together, and between the different management practices performed each year of the project for each treatment. The comparison of means was done by using Tukey–Kramer HSD test with $\alpha = 0.05$. The response variables were the emergence, soil elements, plant measurements, and yield.

Results

Maize yield results

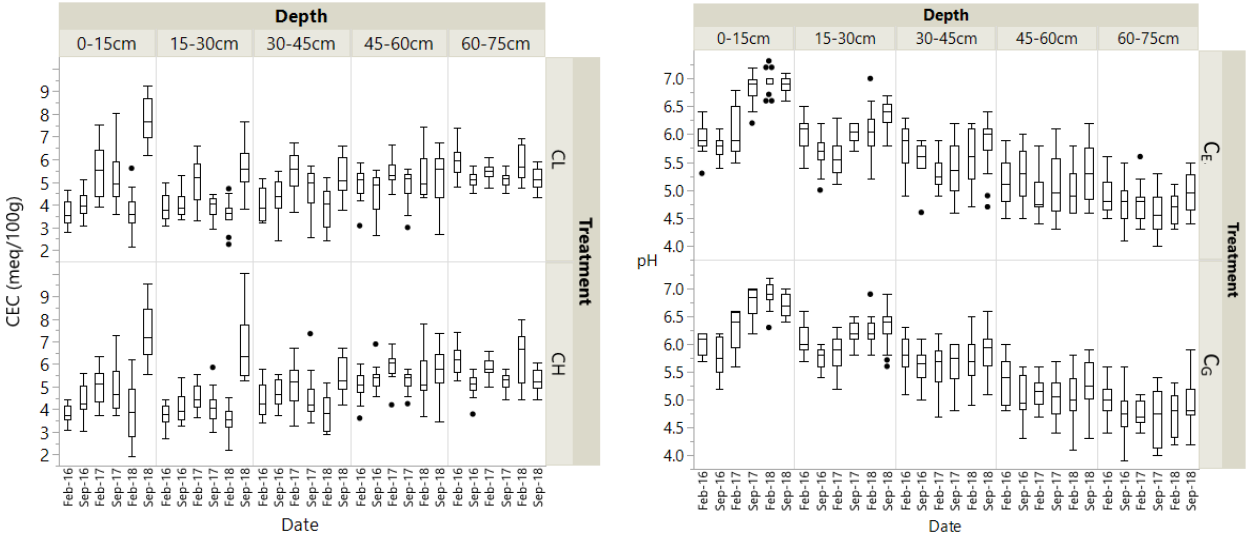
Although the C_E and C_G fertilizer recommendations were based on achieving maize yields of 22 Mg ha^{-1} and 28 Mg ha^{-1}, respectively, the yield results did not exceed 16 Mg ha^{-1} in either of the treatments and growing seasons. Additionally, no significant differences were observed between the two treatments either during each year of the study separately or by combining the three years of the project together (Table 2.3). The C_E treatment had similar yields between 2016 and 2017 growing seasons ($p - value = 0.4067$) as well as between 2017 and 2018 growing seasons ($p - value = 0.0532$). As for the C_G treatment, the yield of 2016 season was statistically greater than the 2017 ($p - value = 0.0207$) and the yield of 2017 was significantly greater than 2018 ($p - value = 0.0179$). The 2016 season had significantly greater yield results compared to the 2018 growing season for both treatments ($p - value_{C_E} = 0.0029$, ($p - value_{C_G} < 0.0001$). The interaction between fertilizer treatment and year had a significant effect on the final yield ($p - value < 0.0001$). Important factors that might have influenced the yield results include environmental and meteorological conditions as well as the management practices followed in each growing season.

Table 2.3 Yield results of C_E and C_G treatment during 2016, 2017 and 2018 growing seasons. Means followed by different letters between fertilization treatments within the same growing season, between fertilization treatments, and between growing seasons within the same fertilization treatment are significantly different ($p - value < 0.05$).

Year	**Treatment**	**Yield (kg ha^{-1})**
By fertilization treatment		
2016	C_E	15223^a
	C_G	16032^a
2017	C_E	14540^a
	C_G	14641^a
2018	C_E	13239^a
	C_G	13219^a
Mean	C_E	14334^a
	C_G	14631^a
By growing season		
2016	C_E	15223^a
2017		14540^{ab}
2018		13239^b
2016	C_G	16032^a
2017		14641^b
2018		13219^c

Soil elements

The Cation Exchange Capacity (CEC) levels were low in all of the plots, which is typical for a sandy soil type (Figure 2.5 and APPENDIX A). The mean CEC values ranged from 3.6 meq 0.01g^{-1} to 7.8 meq 0.01g^{-1}. Low CEC values limit the ability of the soil to hold exchangeable cations. Additionally, soils with low CEC have low organic matter (OM) content, which is another yield limiting component. Before the 2017 and 2018 growing seasons, lime was applied to the NESPAL field, which helped to increase the pH in the shallowest soil layer (0-0.15 m). This increase in pH resulted in significant increases in CEC. However, based on the soil test results (APPENDIX A), the lime could not reach the deepest examined soil layers (up to 0.75 m), which resulted in statistically significant lower values compared to the shallowest soil layers. The tillage is important for lime to move downward, with no deep tillage systems the process is slowed. The soil pH for maize production should be between 5.5 to 7. The mean values ranged from 5.8 to 6.9 in the first 0.15 m depth and from 5.6 to 6.4 in the 0.15-0.3 m depth. The pH was decreased in deeper layers as it is shown in Figure 2.5(b) and it reached the range from 4.6 to 5 in the 0.6-0.75 m depth. Generally, there were cases that the pH was below the optimum values of 5.5 to 7 in depths below 0.3 m. This indicates that from 0.3 to 0.75 m depth the soil was too acidic for maize roots, which can reach up to 1.8 m depth (Feldman, 1994) and it is not unusual to reach even up to 2.4 m (Weaver and Bruner, 1926). Acidic soils may affect maize health indicating nutrient deficiency, even if the soil has plenty of nutrients. Generally, it was observed that the mean values of most of the macronutrients and micronutrients in the soil were statistically greater at the shallow depths than the bottom of the examined soil profile (APPENDIX A).



(a) (b)

Figure 2.5 (a) CEC and (b) pH for each soil layer between 0 m and 0.75 m per soil sampling event for C_E and C_G treatments.

Meteorological conditions

The meteorological conditions played an important role on the final yield results (Figure 2.6, Figure 2.7 and Table 2.4). Although the daily minimum temperatures of the 2018 growing season were below 15 ^{o}C from 0 to 50 days after planting (DAP), they increased above 20 ^{o}C during the rest of the growing season. High nighttime temperatures (above 20 ^{o}C) can increase respiration, which results in decreased yields because less sugars are available for grain filling. Cooler night temperatures prolong the GDDs accumulation, which can lead to greater dry matter development and potentially increase maize yields. During the 2016 and 2017 growing seasons cooler daily minimum temperatures were observed from 50 DAP until the end of the growing seasons. It should be mentioned that the early reproductive stages were observed during June in each growing season. After May, the solar radiation was greater during the 2016 growing season compared to the other two years. The 2018 growing season had the lowest solar radiation which also correlates to it having the highest amount of precipitation. Inadequate solar radiation during the early grain filling and kernel development periods can result in reduced kernel weight and number of kernels per ear. The lower solar radiation and greater minimum temperatures of 2018 growing season led to significantly lower yield results compared to 2016 season ($p - value_{C_E} = 0.0029$, $p - value_{C_G} < 0.0001$). Even if the 2017 growing season had similar temperatures as the 2016, the lower solar radiation and precipitation led to less yields, which in the C_G treatment was statistically significant ($p - value_{C_E} = 0.4067$, $p - value_{C_G} = 0.0207$).

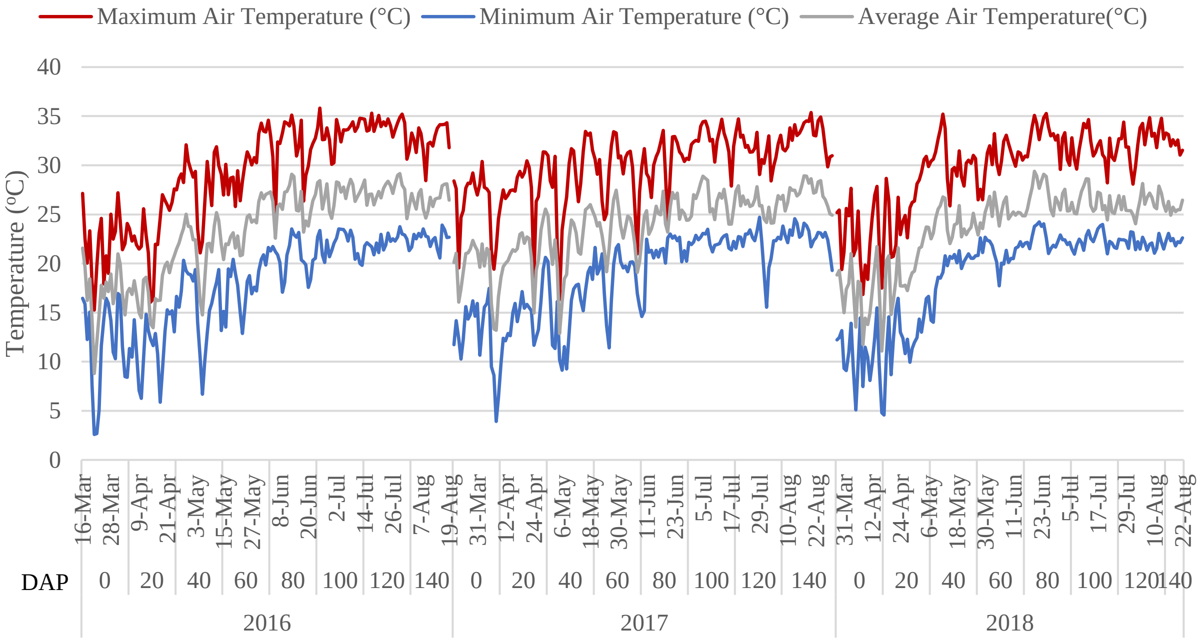


Figure 2.6 Daily maximum, minimum, and average air temperatures during the 2016, 2017 and 2018 growing seasons. DAP are presented on the x-axis.

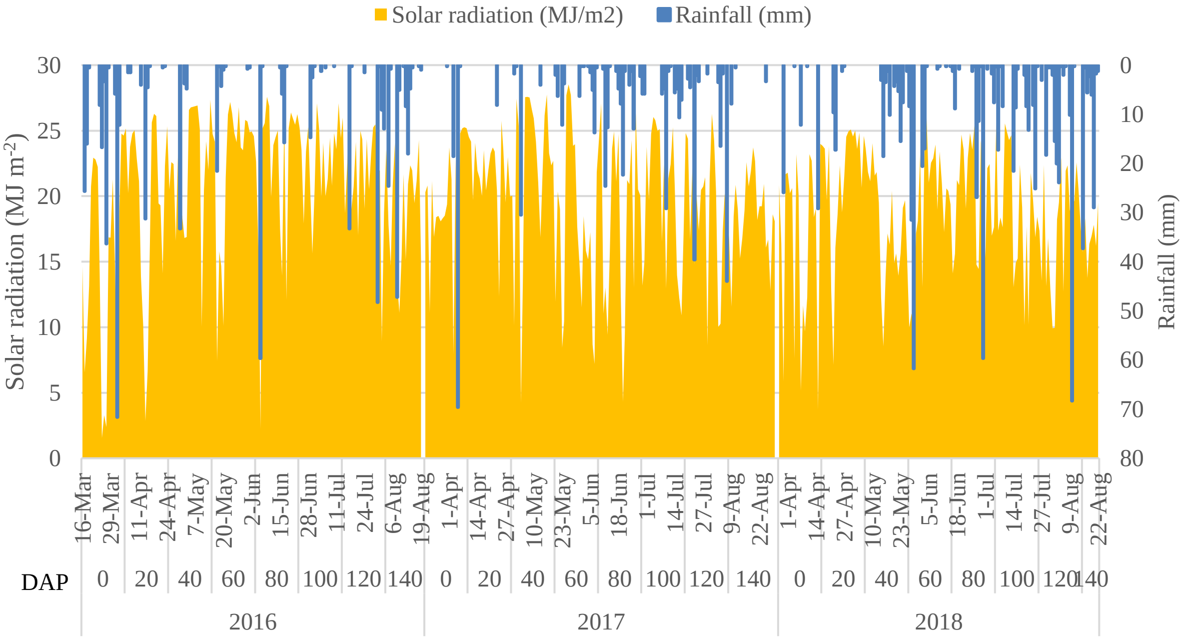


Figure 2.7 Total daily solar radiation and rainfall during the 2016, 2017 and 2018 growing seasons. DAP are presented on the x-axis.

Table 2.4 Average daily air temperatures, solar radiation and cumulative GDDs and monthly precipitation during the 2016, 2017 and 2018 growing seasons.

Year	**Month**	**Cumulative GDDs (ºC)**	**Min temperature (ºC day^{-1})**			**Max temperature (ºC day^{-1})**			**Avg temperature (ºC day^{-1})**			**Solar radiation (MJ m^{-2} day^{-1})**	**Total precipitation (mm)**
			Min	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**		
2016	Mar*	0-108	2.59	16.93	11.78	15.26	27.21	21.84	8.80	21.58	16.76	13.94	113.02
	Apr	109-372	5.88	20.33	12.86	16.05	32.09	24.36	13.46	25.03	18.51	19.65	161.03
	May	373-754	6.69	27.21	22.36	21.07	34.31	28.70	14.75	27.21	22.36	22.19	36.83
	Jun	755-1211	17.07	23.52	20.87	24.34	35.82	32.34	22.59	29.10	26.33	22.11	100.08
	Jul	1212-1711	19.82	23.76	22.20	30.27	35.31	33.98	25.90	29.14	27.51	22.83	85.85
	Aug*	1712-2018	20.56	23.90	22.48	28.44	34.32	32.54	24.55	28.11	26.45	18.46	133.08
	Total	**2018**	**Avg: 17.97**			**Avg: 29.37**			**Avg: 23.32**			**Avg: 20.52**	**629.88**
2017	Mar*	0-102	10.28	16.19	13.84	19.54	29.22	26.70	16.07	22.35	20.25	18.30	0.25
	Apr	103-422	3.91	20.63	13.82	18.56	31.36	27.21	13.21	25.55	20.46	21.35	96.52
	May	423-799	9.13	21.92	16.34	16.32	33.44	28.89	12.87	27.46	22.51	21.18	67.31
	Jun	800-1240	14.59	23.01	20.44	20.97	33.54	29.90	19.08	27.35	24.33	17.06	129.79
	Jul	1241-1741	19.08	24.71	22.40	27.90	34.73	32.35	24.01	28.89	26.47	20.18	123.70
	Aug*	1742-2209	15.54	24.57	22.33	28.41	35.36	32.62	24.11	28.93	26.74	18.27	77.47
	Total	**2209**	**Avg: 18.70**			**Avg: 29.95**			**Avg: 23.83**			**Avg: 19.54**	**495.04**
2018	Mar*	0-20	9.32	13.18	11.79	19.39	25.43	22.81	15.00	19.28	17.54	16.19	25.91
	Apr	21-247	4.57	16.44	10.87	16.84	28.66	23.42	11.09	21.74	17.30	18.20	70.35
	May	248-682	12.44	22.69	18.91	25.88	35.22	29.99	20.51	26.77	23.81	18.25	175.51
	Jun	683-1158	17.74	24.25	21.72	29.07	35.29	32.25	23.82	29.39	26.31	20.96	150.11
	Jul	1159-1658	20.96	23.98	22.35	28.22	34.65	31.76	24.42	28.62	26.19	18.34	146.82
	Aug*	1659-2009	20.22	23.17	22.07	28.09	34.86	32.44	24.05	28.16	25.99	17.80	226.58
	Total	**2009**	**Avg: 18.87**			**Avg: 29.67**			**Avg: 23.67**			**Avg: 18.69**	**795.28**

*Data refer to the dates of the maize growing seasons, i.e.16 Mar 2016 – 19 Aug 2016, 21 Mar 2017 – 29 Aug 2017 and 28 Mar 2018 – 22 Aug 2018.

Emergence

The data presented in Figure 2.8 and Table 2.5 show that the emergence was not a limiting factor in this study regardless the year. The plants began to emerge on the 23rd of March 2016, 26th of March 2017 and 3rd of April 2018, i.e. 7, 5 and 6 DAP during the 2016, 2017 and 2018 growing seasons respectively and the first observation was at 07:00 PM for all the years. The date and time of the first emergence is shown in the graph as 0 h and the observations continued every 12 h until there was 100% emergence. The cumulative GDDs (^{o}C) presented on the x-axis were calculated from the planting day. During the first two growing seasons, the plants in the C_G treatment had a slightly faster emergence than C_E, while the opposite happened during the third year. More specifically, regarding C_E treatment, the plants reached 100% emergence at 5, 4.5 and 2.5 days after the first plant emerged during 2016, 2017 and 2018 growing seasons respectively, while the plants in the C_G treatment reached 100% emergence 3, 2.5 and 4 days after first emergence. The GDDs for 100% emergence were between 66 ^{o}C and 103 ^{o}C for the C_E treatment and between 65 ^{o}C and 74 ^{o}C for the C_G treatment. The yield results were not significantly different ($0.2113 \leq p - values \leq 1$) between the time of emergence for neither of the two fertilization treatments and years of the project (Table 2.5). Even if plants emerged faster, it did not mean that the yield was greater. Based on these results, 100% emergence was achieved in a relatively short time interval for both treatments during each growing season, which led to a good stand and consequently it was beneficial for maize yields. The seeding rate at planting was increased for the C_G treatment to 97850 plants ha^{-1} in the 2018 growing season. Even if a good stand at emergence was observed, the extra number of plants combined with the low solar radiation might have led to intra-row competition and lower yields.

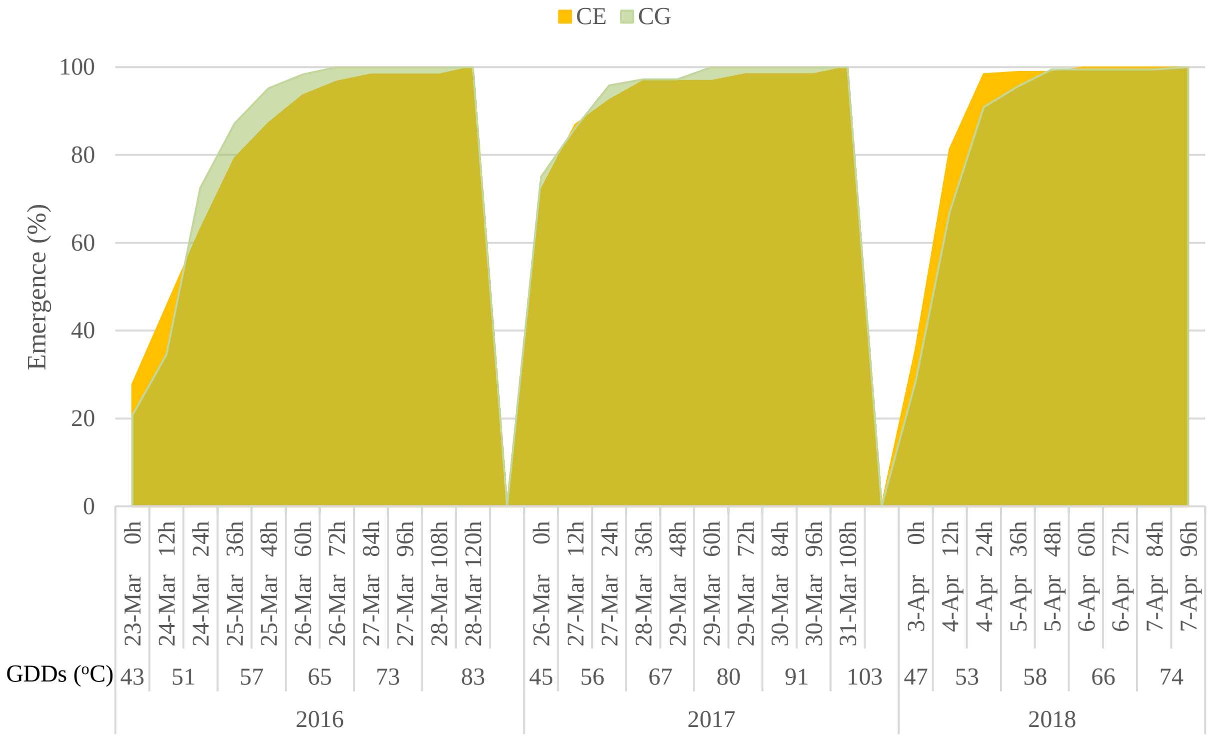


Figure 2.8 Cumulative percentage of plants emerged over 12 h intervals and cumulative GDDs until 100% emergence. GDDs and time of emergence are presented on x-axis.

Table 2.5 Yield response to the time of emergence for C_E and C_G treatment during the 2016, 2017 and 2018 growing seasons.

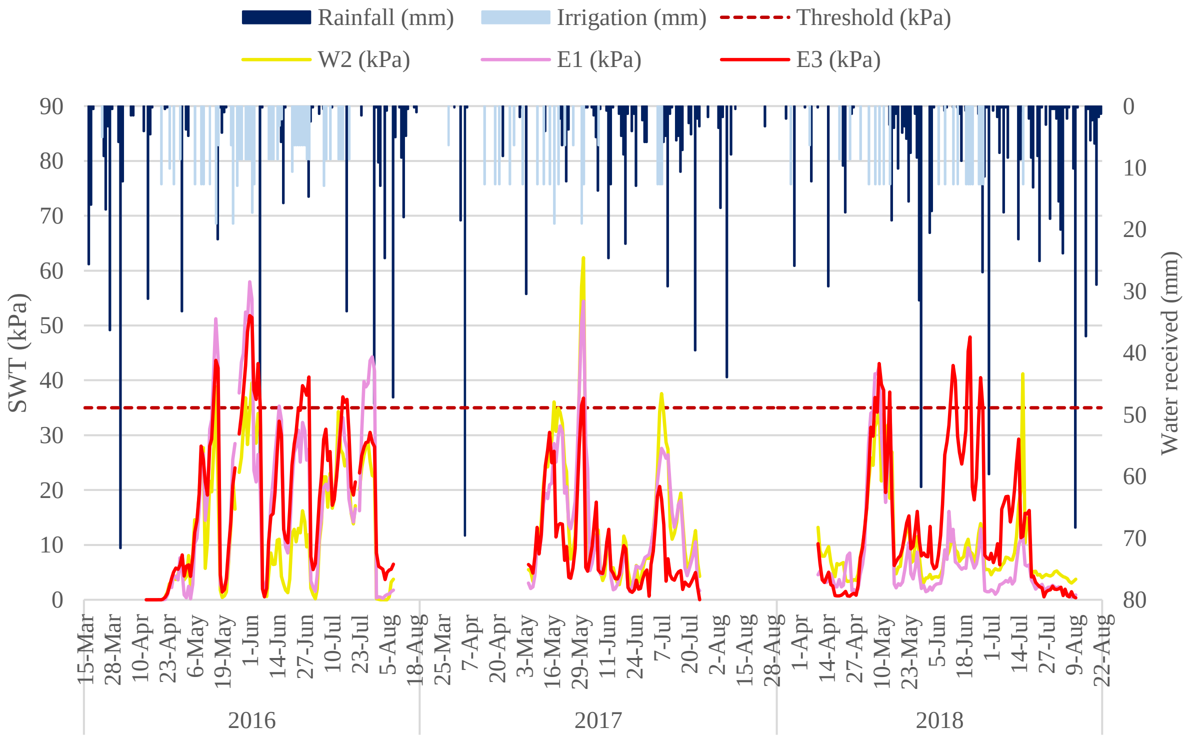
Treatment	**Time (h)**	**2016**	**2017**	**2018**	**Mean**
		Yield (kg ha^{-1})			
By time of emergence					
C_E	0	14921^{a}	14690^{a}	14516^{a}	14635^{a}
	12	15024^{a}	13163^{a}	13713^{a}	13800^{a}
	24	16077^{a}	11755^{a}	13472^{a}	13956^{a}
	36	14060^{a}	12983^{a}	15607^{a}	13939^{a}
	48	16633^{a}	N/A	N/A	16633^{a}
	60	16141^{a}	N/A	8367^{a}	14586^{a}
	72	13562^{a}	N/A	N/A	13562^{a}
	84	16256^{a}	N/A	N/A	16256^{a}
	96	N/A	N/A	N/A	N/A
	108	N/A	12956^{a}	N/A	12956^{a}
	120	14639^{a}	N/A	N/A	14639^{a}
C_G	0	17413^{a}	14357^{a}	13449^{a}	14215^{a}
	12	16357^{a}	14121^{a}	12800^{a}	13201^{a}

Treatment	Time (h)	2016	2017	2018	Mean
		Yield (kg ha^{-1})			
	24	17147^{a}	16034^{a}	13220^{a}	14430^{a}
	36	14483^{a}	11699^{a}	13370^{a}	13809^{a}
	48	18543^{a}	N/A	13399^{a}	15378^{a}
	60	18030^{a}	11721^{a}	N/A	14876^{a}
	72	20622^{a}	N/A	N/A	20622^{a}
	84	N/A	N/A	N/A	N/A
	96	N/A	N/A	N/A	N/A
	108	N/A	N/A	5631^{a}	5631^{a}
	120	N/A	N/A	N/A	N/A

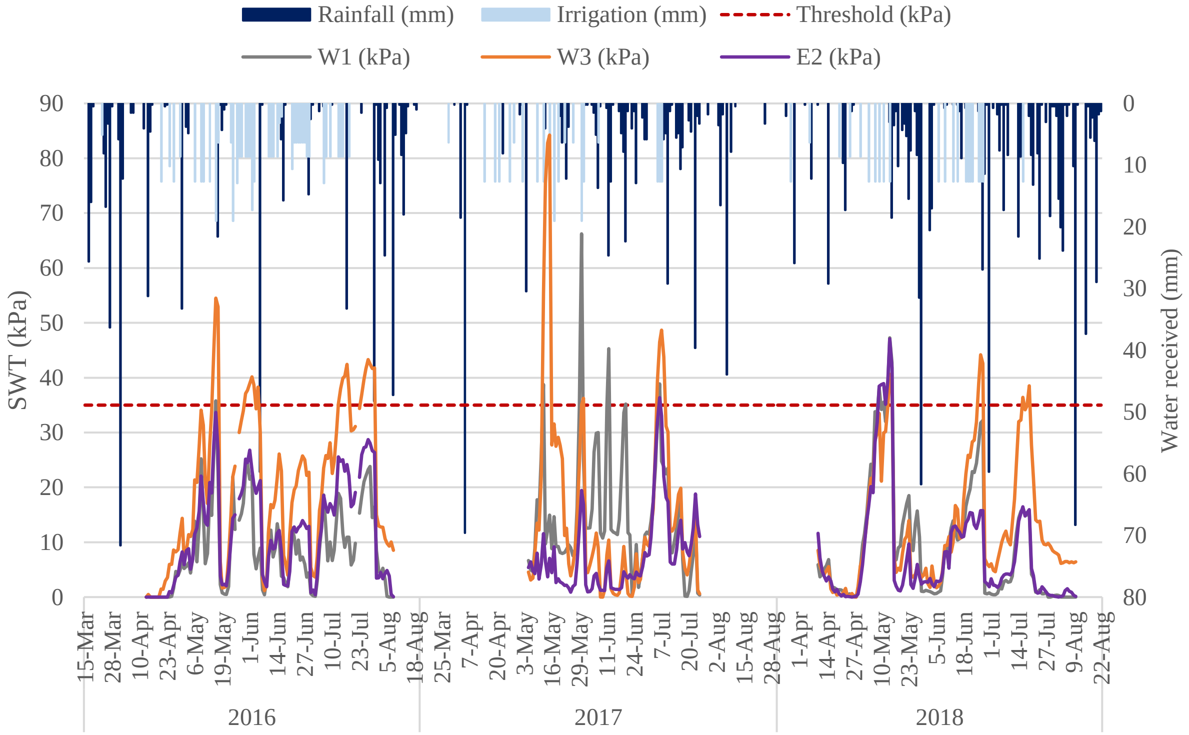
SWT and irrigation

Soil moisture sensors were installed during the early vegetative stages of maize, between V1 and V4, and removed a few weeks before harvest, which explains the gaps with no data at the beginning and end of each growing season in the graphs (Figure 2.9). There are, also, a few gaps with no data during the growing seasons which are due to failure of the soil moisture sensor system. The red dashed line represents the threshold of 35 kPa for scheduling irrigation events for each treatment. The SWT dropped when a rainfall and/or irrigation event took place, while it increased when plants were using water and there was nothing applied or received. In all the three years, there were periods that the SWT was greater than 35 kPa. In 2016, this could have occurred due to crusting issues which resulted in reduced water infiltration and excessive runoff. Another possible explanation is the location of the soil moisture sensors which were placed in the middle of the maize rows in all the three growing periods. It is likely the maize canopy shed the water away from the rows towards the furrows since the pivot sprinklers were well within the canopy. This is something that could stress the plants and influence the final maize yield. However, before and during these periods there were irrigation and rainfall events. This means that even if there were efforts to provide the needed water for the plants the SWT was not dropping. The soil moisture sensors responded better to rainfall events rather than irrigation.

Irrigation was triggered when at least one of the blocks indicated dry conditions. In each irrigation event, the whole field was irrigated. This might be one more possible reason that could have affected the yield results. Table 2.6 shows the total amount of water received through rainfall or irrigation for each maize growing season. The amount of water applied through irrigation was decreased by 42% from 2016 to 2017 and 36% from 2016 to 2018. These results were mainly due to management intensification, which promoted infiltration and a 27% increase in rainfall from 2016 to 2018, which resulted in a lower total amount of irrigation applied.



(a)



(b)

Figure 2.9 Daily average SWT and total amount of water received through applied irrigation or rainfall during the 2016, 2017 and 2018 growing seasons for (a) C_E and (b) C_G blocks.

Table 2.6 Total amount of water received through rainfall and irrigation during the 2016, 2017 and 2018 growing seasons.

Year	Rainfall (mm)	Irrigation (mm)	Total (mm)
2016	629.9	407.7	1037.6
2017	495.0	235.0	730.0
2018	797.3	260.9	1058.2

NUE

The fertilizer rates were excluded from being the limiting factors for achieving greater yields in this study due to the high N, P, K rates applied in both treatments and lack of significant differences between the yield results. Even if the C_G plots received by an average of 47% more N, 67% more P and 59% more K fertilizer compared to the C_E, the yield results were by average only 2% greater and no statistical differences were observed between the two treatments. This indicates that the extra amount of fertilizer applied in the C_G treatment was not effective or efficient, since it did not help increasing maize yields. In fact, as it is presented in Figure 2.10, there is a strong negative linear relationship between NUE and N applied, which means that lower amounts of N led to greater NUE. The C_E treatment was more efficient than C_G because it received less N but produced similar yield results. NUE (Partial Factor Productivity) is the ratio between the final yield and fertilizer applied and a greater NUE depends on the appropriate use of N fertilizer, i.e. timing and placement.

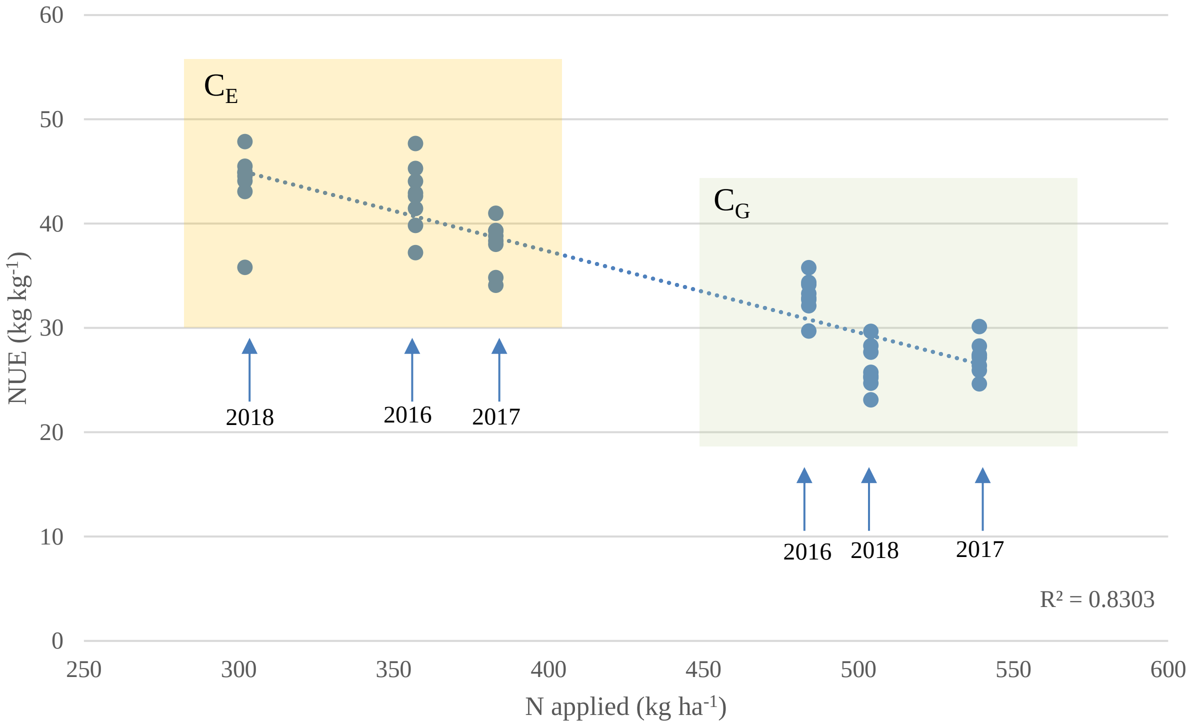
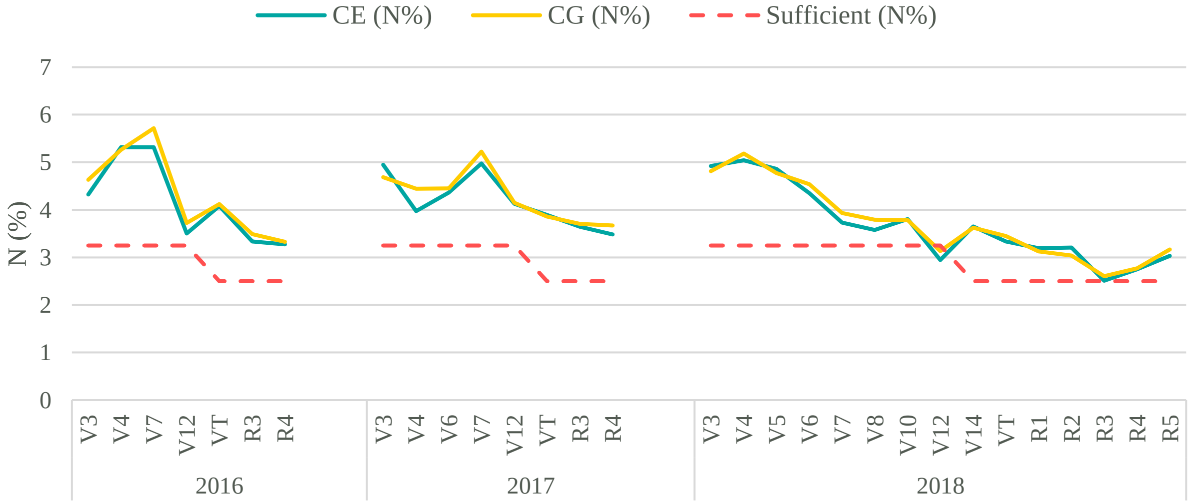


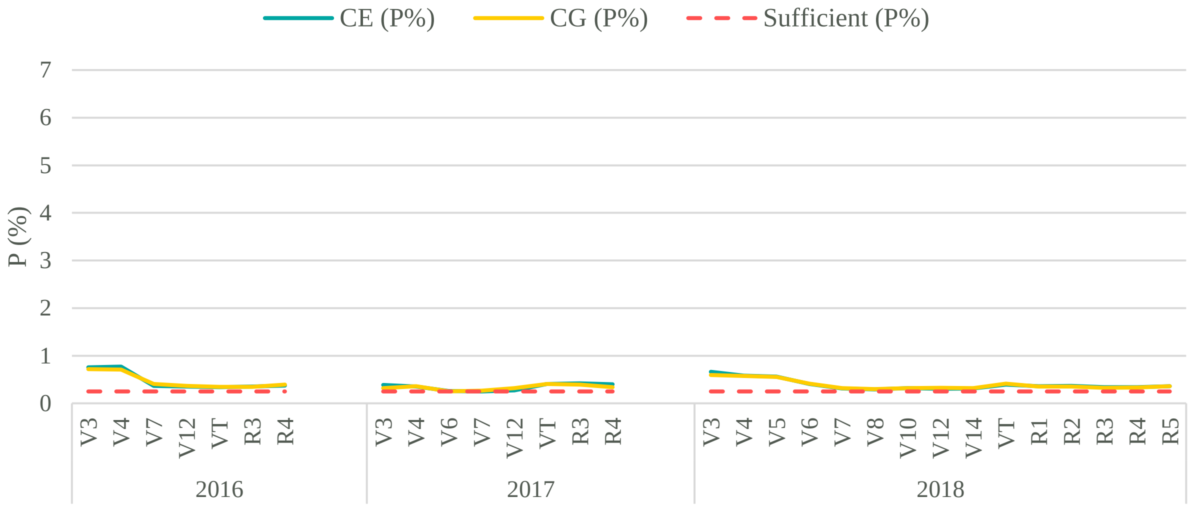
Figure 2.10 NUE of maize during the 2016, 2017 and 2018 growing seasons for C_E and C_G treatment.

Nutrient concentrations

During the three growing seasons, tissue sampling events occurred at several vegetative and reproductive stages to ensure that there were no nutrient deficiencies. All the nutrient concentrations are presented in APPENDIX B, which shows that there were no statistical differences between the two treatments. Although the N concentrations were similar between the three years up to the V6 stage, they decreased statistically in the 2018 growing season after V7 ($p - value < 0.0001$). P is important at the early vegetative stages for the plants to develop a good root system and promote shoot and leaf growth. The 2016 growing season had significantly greater P concentrations compared to the other two years ($0.0036 \leq p - value < 0.0001$), which can contribute to the greater yield in that season. K can assist with leaf growth and crop canopy up to the V6 stage, with yield and protein synthesis from V6 to VT, and maximize growth and yield during the reproductive stages. The 2017 growing season had significantly lower K concentrations during the vegetative stages compared to the other two years ($0.0332 \leq p - value < 0.0001$). No deficiencies of N, P and K concentrations in leaves were noticed throughout the growing season as indicated in Figure 2.11.



(a)



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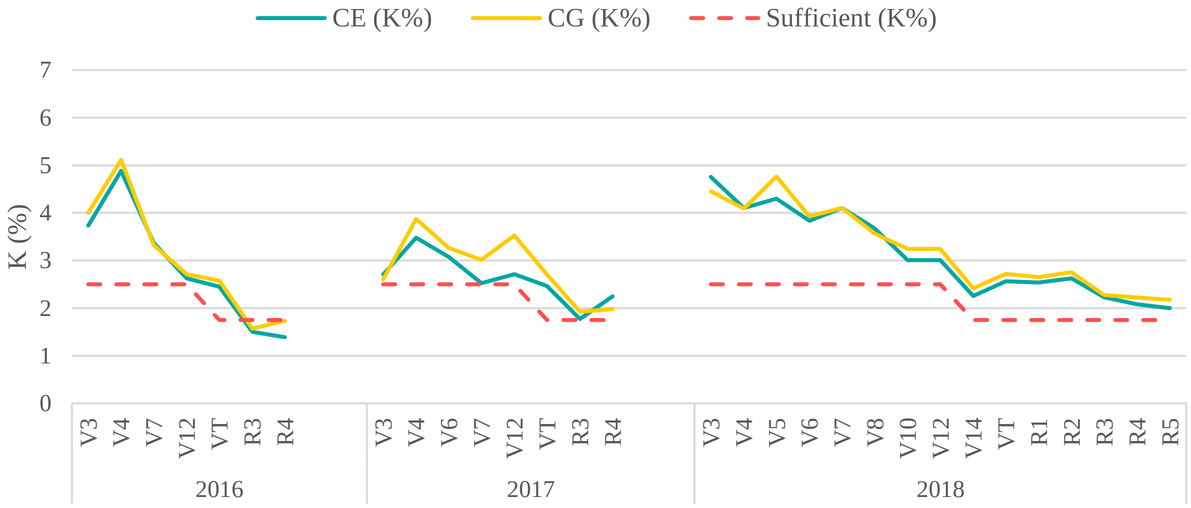

(c)

Figure 2.11 (a) N, (b) P and (c) K leaf concentrations (%) over time during the 2016, 2017 and 2018 growing seasons for C_E and C_G treatments.

Discussion and conclusions

Intensive research efforts to push maize yield to the highest possible limits has been occurring recently around the world. Improved management practices, such as more efficient fertilization, irrigation, seeding rate, plant density and tillage systems, coupled with new hybrids are different approaches for achieving greater maize yields.

Rate of emergence of plants is a factor that is being examined in research studies to identify its correlation to maize yield. In this study, the plants began to emerge 7, 5 and 6 DAP in 2016, 2017 and 2018 respectively, with the GDDs ranging between 43 ^{o}C and 47 ^{o}C. Uniform emergence is important for achieving high maize yields because variation can possibly reduce yield (Liu et al., 2004). In 2016, the yield was significantly greater in comparison to 2018, although the emergence started 1 day later in 2016. The period from onset to final emergence in 2016 lasted for 5 days for the C_E and 3 for the C_G treatment, while in 2018, it took 2.5 and 4 days for C_E and C_G, respectively. This shows that as long as plants emerge in a relatively short time interval, they can establish a good stand, which can lead to good yield results. Similar observations were also made in a 11-year study in Canada, which showed that emergence differences did not lead to lower total dry matter yield, but the climatic conditions could have played an important role in total yield (Dam et al., 2005). Conservation tillage and cover crops can increase the soil water content, which can drop the soil temperature, as it was shown also by Drury et al. (1999), but not to such a degree to affect and slow down the emergence necessarily. Studies have shown that even if uneven emergence of maize plants can result in lower yields, especially as stand density is increased, it is not economically justified and there is no yield benefit to replant just for achieving uniformity (Ford and Hicks, 1992; Nafziger et al., 1991).

There is a tendency to think that by applying more fertilizer more yield will be produced. This is a statement regarding maize that may be true, but only up to a certain level. Although the C_G treatment received by an average 47% more N, 67% more P and 59% more K than the C_E treatment, no significant yield results were observed between the two treatments. This could have happened because, even if there was less fertilizer applied with the C_E treatment, both fertilization levels were high for producing high maize yields. However, a study conducted on maize yield for ten years showed that the high fertilization treatment (516 kg ha^{-1}) produced more in comparison to the two lower fertilization treatments (0 kg ha^{-1} and 258 kg ha^{-1}) (Videnović et al., 2011). The driving force of this study was to increase the maize yield and for that reason the fertilizer applications, for both treatments, were split in multiple applications especially in 2017 and 2018. The idea behind this approach is that by applying smaller amounts of fertilizer at the time that it is needed, there will be less possibilities to lose it through surface runoff or leaching. Although based on the results it seemed that more applications of fertilizer did not produce greater yield results, the weather and soil conditions played an important role to this outcome. In 2016, the fertilizer rate was split in 4 applications, one prior to planting, one at planting and two additional side-dress applications during the season, which is a common grower practice, and this year produced the highest yield. Previous studies have shown that the application of N during the V10 to R2 stages can result in significant yield increases (Binder et al., 2000; Roberts et al., 2016) Moreover, based on Scharf et al. (2002) the application of N fertilizer up to the V11 stage is not going to have negative effects on yield results. In fact, in their study it was shown that by applying fertilizer even later at the V12 and V16 stages there was just a slight yield decrease of 3%.

The plant and soil samples collected through the years showed that there were no deficiencies of the nutrients measured. The N concentration in ear leaves for the C_E and the C_G treatments was 3.1% and 3.2% , respectively. A study which took place in central Washington showed that when the ear leaves had a N concentration of 2.2% to 2.8% the plants did not manage to produce maximum yield even if there were no deficiency symptoms (Viets et al., 1954). Viets et al. (1954), also, showed that only N increased yield significantly in comparison to P, Ca, Mg, K and Mn, while a leaf N concentration of 2.8% at the R1 stage could lead to the best yield results.

In a study by Liang and MacKenzie (1994), maximum maize yields were produced by the application of 300 kg N ha^{-1} to 350 kg N ha^{-1}, although N applications at 285 kg N ha^{-1} and 400 kg N ha^{-1} could not be fully recovered by maize plant uptake. If N is not used by the plants, it is possible to cause environmental problems through runoff and leaching. For that reason, NUE is crucial not only for acquiring high maize yields but also for preventing N from causing environmental pollution. The results from this study showed that there was a negative relationship between the amount of fertilizer applied and NUE (Partial Factor Productivity). The average NUE for C_E treatment was 42 kg grain kg N^{-1} and for C_G treatment 29 kg grain kg N^{-1}. In a study conducted by Austin et al. (2019), the average NUE was 50 for N rates ranged from 179 kg N ha^{-1} to 213 kg N ha^{-1}. The average NUE increased to 63 kg grain kg N^{-1} when the N rate decreased by 25%, while it decreased to 41 kg grain kg N^{-1} when the N rate increased by 25%.

A 20-year study showed that even if the P concentrations fluctuated noticeably during the years of the project, it seemed that when leaf P at silking was greater than 0.3%, there was no yield reduction (Randall et al., 1997). According to Randall et al. (1997), a critical leaf K concentration could not be established, because different hybrids had different leaf K concentration, but maize yields were optimized at concentrations of 2.29%, 1.69% and 1.14% (Randall et al., 1997). The concentration of P and K at silking was measured only during 2018 and it was 0.4% and 2.5%-2.7% respectively, but 2018 was the year with the lowest yield results.

There was more rainfall received during 2018 in comparison to the other two years which could have influenced the yield results as well, since there were more periods of clouds covering the sky which caused the lowest solar radiation of all three seasons. Lower values of solar radiation and increased amounts of water received through rainfall could have played a significant role in observed lower yield results during the 2018 growing season. Similar results were shown by a study in which there was a comparison of different maize cultivars and planting densities, showing that lower solar radiation intensities reduced grain yields (Yang et al., 2019). Similarly to solar radiation, temperature was also lower in 2018 which could have affected the final yield. Lower early season temperatures, as it occurred during 2018, could delay maize development and modify individual leaf area. This correlation was also shown in a 2-year field experiment, in which warmer early season soil temperature linearly increased yield, while maize plants that experienced lower temperatures went through vegetative development faster (Bollero et al., 1996).

For evaluating the periods that the field needed to be irrigated, SWT data were recorded hourly. The SWT was kept below 35 kPa, for most of the growing seasons, but there were periods that this threshold was surpassed. Consequently, the amount of water applied through irrigation can have crucial effects on the final maize yield. More irrigation was applied during the 2016 growing season, and that year produced greater maize yield compared to the other two years of the project. This agrees with the results of Fang and Su (2019), which showed that plots received the highest irrigation achieved greater yields in comparison to other treatments that less irrigation was applied. However, during 2017, 42% less irrigation was applied but the yield results were not statistically different to the 2016 growing season for C_E treatment. Furthermore, even if the 2017 growing season received less water than the 2018, significantly greater yield was produced for C_G treatment.

Studies have shown that it is possible to have greater maize yields when there is a rotation with another crop (Wilhelm and Wortmann, 2004), especially when maize is grown after soybean. It was expected that the yield results would have been greater during 2017 and 2018, not only because of the more intensive management, but also because of the rotation between maize and soybean. The reason for this expectation was because this rotation could increase the net soil N mineralization and increase residual soil N content (Gentry et al., 2001). The yield results were not the ones expected, nonetheless, since 2016 was the year with the highest maize yield in comparison to the other two years.

In conclusion, the yield goals of the C_E and C_G treatments, which were 22 Mg ha^{-1} and 28 Mg ha^{-1}, respectively, were not achieved during any of the growing seasons of this study, which was conducted in Tifton, GA. Reasons for not achieving the yield goals were the sandy soil of the field, which was low in CEC and pH, and the meteorological conditions. The higher solar radiation and lower minimum temperature during the 2016 growing season, resulted in significant higher yields compared to the 2017 and 2018 growing seasons. The N rates for both C_E and C_G treatments were high enough, which resulted in no significant differences in terms of yield between the two treatments.

CHAPTER 3

APPLICATION OF DSSAT CERES-MAIZE MODEL FOR SIMULATING HIGH INPUT MAIZE PRODUCTION[2]

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[2] Orfanou, A., D. Pavlou, G. Vellidis, K.J. Boote, and W.M. Porter. To be submitted to *Agronomy Journal*.

Abstract

Meteorological, soil and plant data were collected during a three-year study (2016-2018) conducted in the southeastern Coastal Plain of Georgia, USA for simulating high input maize production with the DSSAT-CERES-Maize model. Two high fertilization treatments were included in the field study and each treatment had eight replications. Each replication was simulated separately due to the variability in the soil type and plant density at harvest. The 2018 dataset was used for calibrating the CERES-Maize cultivar coefficients P1, P2, P5, G2, G3 and PHINT by simulating leaf number per stem, leaf weight, vegetative N concentration and yield. The model was evaluated by applying the datasets of the 2016 and 2017 growing seasons. The results showed that the model was successfully calibrated with high correlation values and d-stat (>0.8). The evaluation of the model also provided a good fit between simulated and observed data. The observed data were different for each replication, which explains the differences in statistics per replication. However, the model output was not different per replication within the same treatment. In conclusion, DSSAT-CERES-Maize model was successfully used for simulating maize production under high input management practices in Coastal Plain of Georgia.

Introduction

An agricultural system includes all the components related to the production of crops, food, fiber, and energy. Field experiments are important for studying an agricultural system, i.e. understanding crucial plant characteristics, their relationship with soil and water and the potential impact they could have on the environment, comparing new with old methods and improving agricultural practices and equipment (Johnston, 1997; Mitchell et al., 2008; Payne, 2006; Tabatabaeefar et al., 2009). Field experiments essentially represent components of different systems and can produce solutions and insights for the development or the adjustment of management practices which can lead to higher yields and profits as well as improving environmental quality. However, even if the benefits of field experiments can be valuable, there are also some drawbacks. Sometimes, there are processes which are very difficult to be measured in a physical environment. Time is needed for collecting and analyzing data for reaching a conclusion. Furthermore, unpredicted situations, such as weather conditions or human errors, might result in more uncertainty and error in the experiment. Thus, a model is a necessity for assessing a system, understanding its behavior and predicting its performance (Jones et al., 2017).

History of simulation modeling in agriculture

The work on agricultural systems modelling began in the 1950s (Jones et al., 2017). One of the first approaches was by Heady (1957) who tried to run an econometric investigation of several cases at a farm scale level for evaluating them and seeing the potential benefits. An important turn in history of modelling was the creation of the International Biological Program (IBP) by ecological scientists who wanted to have tools that would allow them to study factors that affect the ecosystems (Van Dyne and Anway, 1976; Worthington, 1975). The work of de Wit and Duncan (de Wit, 1958; Duncan et al., 1967), two of the pioneers in agricultural systems modelling, was the spark for using and developing crop models. As it happened with IBP initiative, the first crop models were created by scientists from different backgrounds who came together to work on problems trying to solve them through a mathematical way. However, many agricultural scientists were skeptical of the value of models. During the same period, the Soviet Union purchased large quantities of USA wheat (Pinter Jr et al., 2003). The short-term result of that action was the increase in wheat prices and shortages, while the long-term result was the new research programs that were funded for the creation of models such as CERES-Wheat and CERES-Maize (Jones, 1986; Ritchie and Otter, 1985), for the prediction of trends for crops that were produced internationally. Both CERES-Wheat and CERES-Maize models belong into the Decision Support System for Agrotechnology Transfer (DSSAT) family of models (Hoogenboom et al., 2012; Jones et al., 2003). Agricultural system models have been developed to be used in a wide range of application over the last years including crop and livestock systems (Lilley and Moore, 2009), yield gap analysis (Hochman et al., 2013), plant breeding (Messina et al., 2010), climate change (Elliott et al., 2013), water quality (Ahmed et al., 2007), resource use and efficiency (Qureshi et al., 2013), bioenergy (Persson et al., 2010), agricultural tool development (Busato et al., 2013), food security (Carberry et al., 2013), optimization (Orfanou et al., 2013), supply chain management (Pavlou et al., 2016) etc.

Important simulation models in agriculture

The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project led to the creation of DSSAT (IBSNAT, 1993; Jones et al., 2003; Tsuji et al., 2013), which is supported by data base management programs for soil, weather, crop management and experimental data, and by utilities and application programs. DSSAT includes over 42 crop simulation models that have been used to characterize, simulate, and assess field crop production practices. DSSAT is used by scientists for various applications such as irrigation (Panda et al., 2004), improved water use (Lobell and Ortiz-Monasterio, 2006), fertilizer and pest management applications (Cabrera et al., 2007), etc. DSSAT CERES-Maize was used by Liu et al. (2011b) for the simulation of maize yield and N dynamics under long term (50 years) continuous maize production in Canada. The data from a 2 years study in Thailand were used in DSSAT CERES-Maize model for the simulation of nitrate leaching, maize grain yield and soil moisture content (Asadi and Clemente, 2003).

Besides DSSAT, there are also other important agricultural models that have been used for different applications, such as the Environmental Policy Integrated Climate (EPIC), Agricultural Production Systems Simulator (APSIM), Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS), World Food Studies (WOFOST), ORYZA, Cropping Systems Simulation Model (CROPSYST), Root Zone Water Quality Model (RZWQM), Tradeoff Analysis (TOA), International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), Statewide Agricultural Production (SWAP) and Global Trade Analysis Project (GTAP). For instance, the EPIC model was used by Izaurralde et al. (2006) for describing new C and N modules to connect the simulation of soil C dynamics to crop management, tillage and erosion. The APSIM model was used to simulate wheat, maize and fieldpea monocultures as well as a maize/wheat and maize/ fieldpea strip relay intercropping system (Knoerzer et al., 2011). The RZWQM has been used by Ahmed et al. (2007) for simulating long term effects of N management in southern Ontario conditions.

Decision support systems

A simulation model can be used as a Decision Support System (DSS) for improving the crop management practices and consequently crop production. However, for this tool to provide accurate insights to the grower and/or scientist, the calibration and evaluation of the model is particularly important. Calibration is needed when the model is applied to new locations, when new cultivars, varieties and hybrids are used because they have not been parameterized for most models, and because the models have been updated and improved over the time (Holzworth et al., 2015). Evaluation is important for documenting the accuracy of the model, as well as, potential uncertainties that the model could have. Saseendran et al. (2008) calibrated and validated the CERES-Maize model to assess irrigation scenarios that have potential to optimize water use efficiency during the crop growth period. O'Neal et al. (2002) used 5 years (1995-1999) of data for calibrating and validating the DSSAT CERES-Maize model for determining special and temporal precipitation variability and its effect on maize yield. A successful calibration and evaluation of a simulation model can provide economic benefits along with environmental benefits. This model then can be used for comparing management practices in order to identify the more beneficial ones and the prediction of the outcome of crop production systems (Jones et al., 2003; Saseendran et al., 2007).

Goals and objectives

The goal of this project was to calibrate and validate the DSSAT CERES-Maize model by using experimental data, i.e. soil, crop and weather, collected from a field in South Georgia for three years (2016-2018) under typical production practices encountered by Georgia maize growers. The 2018 data were used for calibrating the model while the other two years for its evaluation.

Materials and methods

Field experiment description

This work was based on a field study conducted in a field located at the University of Georgia’s Tifton Campus (31°28’44.05” N, 83°31’55.00” W), in Tifton, GA, from 2016 to 2018, by (Orfanou et al., 2020a). The Tifton Campus is located at the Tifton-Vidalia Upland portion of the Gulf-Atlantic Coastal Plain. The climate of the area is humid subtropical. According to the University of Georgia Weather Network (UGAWN; http://weather.uga.edu/), the average maximum and minimum temperatures are 25.17 °C and 12.72 °C, respectively, and the average annual precipitation is 1208 mm based on 93-yr mean annual data. The warmest months of the year are from March to August, which is the typical period of maize production in the Southeastern Coastal Plain of Georgia, USA. These months receive the most precipitation as well.

The field, which was 1.44 ha, was separated into six blocks (W1, W2, W3, E1, E2, E3) and each block was separated into smaller plots depending on its size having in total thirty-two plots (Figure 3.1). The field consists of two soil series, Tifton loamy sand and Alapaha loamy sand. Tifton loamy sand covers the most area of the field on the west side, while Alapaha loamy sand is observed on half of the area of the eastern E1, E2, and E3 blocks. Both soil types are characterized as acidic, low in organic matter and natural fertility according to NRCS Soil Survey (https://www.nrcs.usda.gov/). Tifton loamy sand is deep and well drained. Alapaha loamy sand is also deep but poorly drained.

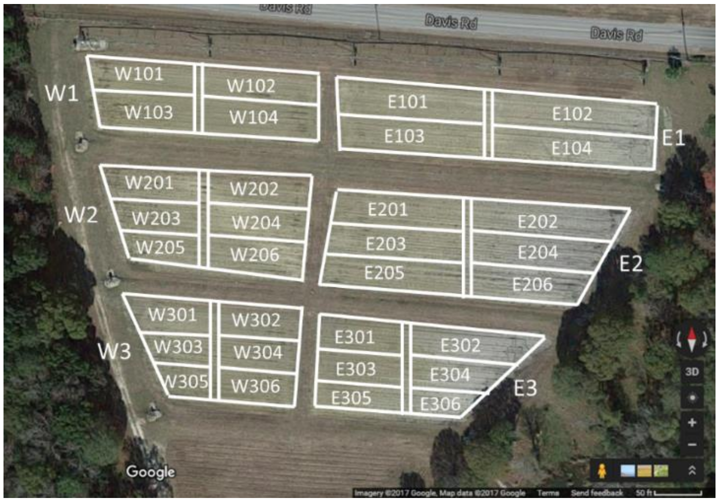
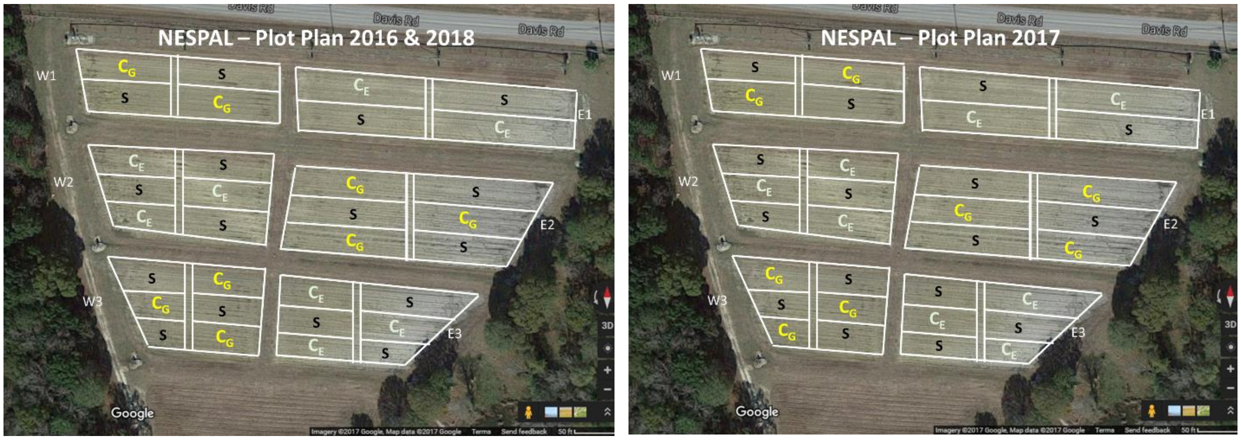


Figure 3.1 Graphical representation of the field, blocks, and plots.

Half of the plots were planted with maize (Zea Mays), variety P1794VYHR (Pioneer, Johnston, IA, USA), indicated with C_E and C_G in Figure 3.2. The C_E and C_G refer to the two fertilization treatments of the study. The C_E treatment had as a yield goal of 22 Mg ha^{-1} and it was recommended by the UGA Extension Service. The C_G treatment was recommended by the Georgia Maize Growers for yield goal of 28 Mg ha^{-1}. The total amount of fertilizer applied per treatment during each growing season is shown in Table 3.1. There were eight replicates of each treatment (Figure 3.2). The rest of the plots were planted with soybean (Glycine max) for proper crop rotation between the three growing seasons, indicated with S in Figure 3.2. However, the focus of this study was on the sixteen maize plots and no fertilizer was applied to soybean plots.



(a) (b)

Figure 3.2 Plot plans of NESPAL field indicating the location of soybeans (S) and maize (C_E and C_G fertilization treatments) plots during the (a) 2016 and 2018, and (b) 2017 growing seasons.

Table 3.1 Fertilizer rates and application dates for C_E and C_G treatments during the 2016, 2017 and 2018 growing seasons.

Year	**Type**	**Date**	**C_E**			**C_G**		
			N	**P_2O_5**	**K_2O**	**N**	**P_2O_5**	**K_2O**
			kg ha^{-1}					
2016	Preplant	15 Mar	110	67	191	110	200	370
	At planting	16 Mar	47	45	N/A	47	45	N/A
	Side-dress	8 Apr	100	N/A	N/A	110	N/A	N/A
	Side-dress	25 Apr	100	N/A	N/A	230	N/A	N/A
	Total		**357**	**112**	**191**	**497**	**245**	**370**
2017	Preplant	15 Mar	90	146	291	90	213	404
	At planting	21 Mar	48	44	N/A	48	44	N/A
	Side-dress	13 Apr	123	N/A	N/A	123	N/A	N/A
	Side-dress	21 Apr	123	N/A	N/A	63	N/A	N/A
	Side-dress	2 May	N/A	N/A	N/A	63	N/A	N/A
	Side-dress	12 May	N/A	N/A	N/A	63	N/A	N/A
	Side-dress	26 May	N/A	N/A	N/A	63	N/A	N/A
	Side-dress	2 Jun	N/A	N/A	N/A	27	N/A	N/A
	Total		**383**	**191**	**291**	**540**	**257**	**404**
2018	Preplant	22 Mar	30	101	247	64	202	392
	At planting	28 Mar	48	44	N/A	48	44	N/A
	Side-dress	24 Apr	112	N/A	N/A	112	N/A	N/A
	Side-dress	8 May	56	N/A	N/A	56	N/A	N/A
	Side-dress	23 May	56	N/A	N/A	112	N/A	N/A
	Side-dress	5 Jun	N/A	N/A	N/A	112	N/A	N/A
	Total		**302**	**145**	**247**	**504**	**246**	**392**

Management practices

Table 3.2 presents the management practices followed during each growing season. The initial field conditions were different from year to year. The field was fallow in the winter before maize was planted in 2016, while wheat and rye were utilized as winter cover crops during 2017 and 2018, respectively. Thus, conventional tillage was utilized the first year and conservation (strip till) the following two. Soil samples were also collected from 5 layers (0-0.15 m, 0.15-0.3 m, 0.3-0.45 m, 0.45-0.6 m, and 0.6-0.75 m) for determining the soil initial conditions for each growing season.

After the initial conditions were determined, decisions about the management practices were made (Table 3.2). The dates of planting were determined based on the soil temperature, which had to be at 13 °C. Initially, the plant density at seeding was decided to be 79000 plants ha^{-1} for both treatments. In 2018, it was decided to increase the seeding rate to 97850 only for the C_G treatment with the goal to increase the final maize yield. Random plots were selected for recording emergence data from a 3-m section of row that was assigned for this reason. Emergence data were collected twice per day, at 7:00 AM and 07:00 PM, until there was near 100% emergence observed.

Irrigation was scheduled based on soil moisture sensors located in each one of the maize plots at depths of 0.2 m, 0.4 m and 0.6 m and the irrigation was applied by a central pivot irrigation system. The soil water tension (SWT) was recorded hourly, but irrigation decisions were made based on the SWT readings at 7:00 AM every morning. When the SWT was close to 30 kPa - 35 kPa, the field was irrigated. The irrigation was terminated when maize was at black layer stage, i.e. middle of July.

The harvest took place at the end of August, when the moisture of the kernels had reached approximately 15%, with the University of Georgia Variety Trial Program’s plot-scale grain combine.

Table 3.2 Management practices followed during the 2016, 2017 and 2018 maize growing seasons.

	2016		**2017**		**2018**	
	C_E	**C_G**	**C_E**	**C_G**	**C_E**	**C_G**
Soil core sampling						
Date	22 Feb		6 Feb		5 Feb	
Tillage						
Method	Conventional		Conservation		Conservation	
Planting						
Variety	P1794VYHR		P1794VYHR		P1794VYHR	
Planting date	16 Mar		21 Mar		28 Mar	
Planting density (seeds ha^{-1})	79000	79000	79000	79000	79000	97850
Depth (cm)	5		5		5	
Row spacing (cm)	90		90		90	
Planting method	Bedded		Bedded		Bedded	
Emergence date	23 Mar		26 Mar		3 Apr	
Irrigation						
SWT threshold (kPa)	<35		<35		<35	
Application rate (mm h^{-1})	71		36		36	
Total amount applied (mm)	408		235		261	
Harvest						
Harvest dates	19 Aug		29 Aug		22 Aug	

Experimental data collection

Soil data

Soil core samples were collected every February, prior to planting the maize. During February 2016, the first season, the plot boundaries were not yet defined so a “Z” pattern was followed in which five core samples were collected from each block, i.e. four from each corner and one from the center of the block. The sampling process changed in the following sampling years, in which one soil core sample was collected from the center of each plot, i.e. four to six samples per block. The samples were collected from 0 m to 0.75 m depth and separated by 0.15 m depth increments into five layers. These samples were analyzed for pH in water (pH), pH in buffer (Bf) and Cation Exchange Capacity (CEC) by a commercial laboratory. Further analysis was done for ammonium (NH_4-N), nitrate (NO_3-N), Total Nitrogen (TN) and texture (Clay% and Silt%).

Meteorological data

Daily meteorological data, i.e. maximum and minimum air temperature (^oC), dew point temperature (^oC), precipitation (mm), solar radiation (MJ m^{-2}), relative humidity (%), and wind speed (m s^{-1}), were obtained from the University of Georgia Weather Network (UGAWN). These data are presented in Table 3.3.

Table 3.3 Weather data measured during the maize growing season from 2016 to 2018 in Tifton, GA, where this study was conducted. The growing seasons were from middle of March to end of August (16 Mar 2016 – 19 Aug 2016, 21 Mar 2017 – 29 Aug 2017, and 28 Mar 2018 – 22 Aug 2018).

Season	**Min. temperature (°C)**			**Max. temperature (°C)**			**Dew point (°C)**			**Avg relative humidity (%)**	**Total precipitation (mm)**	**Avg solar radiation (MJ m^{-2})**	**Avg wind speed (m s^{-1})**
	Min	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**				
2016	2.6	23.9	18.0	15.3	35.8	29.4	-1.4	23.9	17.7	73.51	630	20.52	2.10
2017	3.9	24.7	18.7	16.3	35.4	30.0	1.7	24.2	18.5	75.55	495	19.54	2.09
2018	4.6	24.3	18.9	16.8	35.3	29.7	2.2	24.1	18.9	77.25	795	18.69	2.13

Plant and yield data

Scouting and plant sampling events were collected at several vegetative and reproductive stages during the growing seasons. During 2016, plant samples were collected at the stages of V3, V4, V7, V12, VT, R3 and R4. During 2017 and 2018, the number of sampling events was increased. In 2017, samples were collected during the V3, V4, V6, V7, V10, V12, V16, VT, R1, R3, R4 and R6 stages, while during 2018, the samples were collected during the V3, V4, V5, V6, V7, V8, V10, V12, V14, VT, R1, R2, R3, R4, R5 and R6 stages. Measurements such as leaf number, leaf and stem weight and number of kernels per plant were taken. The samples were also analyzed for N by a commercial laboratory, for identifying the N concentration in leaves and stems.

At the end of the growing season, grain yield data at maturity was collected from the middle two rows of each plot, which corresponded to 27.74 m^2 land area per plot (443.83 m^2 total).

Model implementation

The DSSAT CERES-Maize model was used to simulate growth, development and yield as a function of the management practices, soil, plant, and atmosphere dynamics (Figure 3.3).

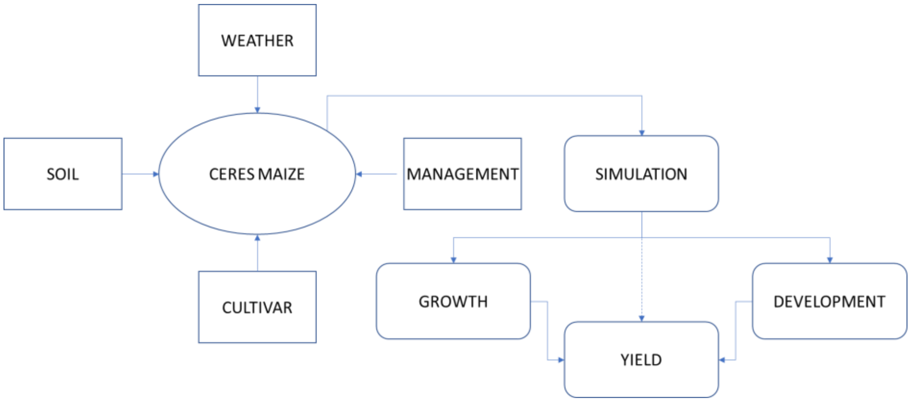


Figure 3.3 Diagram of DSSAT CERES-Maize model

A new maize cultivar was created by adjusting the cultivar coefficients of P1, P5, G2 and PHINT based on the observed data during the 2018 growing season and P2 and G3 based on Bao et al. (2017). P1, P2 and P5 represent life cycle progression, G2 and G3 grain filling and PHINT the phyllochron interval between successive leaf tip appearances. A more detailed description, for each one of the coefficients, is presented in Table 3.4.

Table 3.4 Cultivar coefficients.

Cultivar coefficients	**Description**
P1	Thermal time from seedling emergence to the end of the juvenile phase (GDD)
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (day/h)
P5	Thermal time from silking to physiological maturity (GDD)
G2	Maximum possible number of kernels per plant (kernels/plant)
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)
PHINT	The interval in thermal time between successive leaf tip appearances (GDD)

A new soil profile for each plot was created from the information collected from the soil core samples of February 2018. The values of clay%, silt%, pH, CEC, and TN were used as inputs, while the lower limit of plant extractable soil water (LL), soil water content at drained upper limit (DUL), soil water content at saturation (SAT), root growth factor (RGF), saturated hydraulic conductivity (K_s), and bulk density (BD) were calculated by the DSSAT's pedotransfer function SBUILD (APPENDIX C).

There are some minimum requirements regarding weather data for running the DSSAT model, these include solar radiation (MJ m^{-2}), daily maximum and minimum temperature (°C), and daily precipitation (mm). The WeatherMan tool (Pickering et al., 1994) was used for creating a new weather station based on weather data obtained from UGAWN. The inputs for the weather profile were the daily precipitation (mm), maximum and minimum temperatures (^{o}C), solar radiation (MJ/m^2/day), dew point temperature (°C), wind speed (m s^{-1}), and relative humidity (%).

An experimental file for each maize growing season was created. Each replication of each treatment was simulated separately to increase model performance due to the differences in the soil profile and plant densities at harvest. The characteristics of the field, initial conditions, management practices, cultivar, weather station and soil profile for each replication were the inputs to the model. The simulation start date was on the 1st of February for each growing season.

Model calibration and evaluation

For calibrating the simulation model, experimental (observed) data from the 2018 growing season were used. These data were the leaf number, leaf weight (kg ha^{-1}), grain yield at maturity (kg ha^{-1}) and leaf and stem nitrogen (N) concentration (%) over time. The cultivar coefficients were adjusted so that the simulated curve was as close to observed data as possible. Each cultivar coefficient was adjusted to a value between the minimum and the maximum value described in Table 3.5.

Table 3.5 Maximum, minimum, and initial values for the cultivar coefficients for DSSAT CERES-Maize model.

Cultivar coefficients	**Min value***	**Max value***	**Initial values**
P1	110.00	458.00	300.70
P2	0.00	3.00	0.75*
P5	390.00	1000.00	809.00
G2	248.00	990.00	720.00
G3	4.40	16.50	10.94*
PHINT	30.00	75.00	42.00

*Bao et al., 2017

For validating the model and to ensure that the calibration process was successful, observed data from the 2016 and 2017 growing seasons were used. More specifically, a comparison between the simulated and observed data of leaf number, leaf weight (kg ha^{-1}), grain yield at maturity (kg ha^{-1}) and leaf and stem N concentration was performed. Due to lack of leaf and stem weight data in 2016 growing season, the evaluation process was performed only for leaf number and grain yield at maturity.

Statistical criteria

The performance of the model, when comparing simulated with observed data during calibration and evaluation process, was evaluated by using commonly used statistical criteria and more specifically the coefficient of determination (r^2), root mean square error (RMSE) and index of agreement (d-Stat). The r^2 is defined by Eq. 3.1. The closer the r^2 is to 1, the better the match between simulated and observed data. Similarly, when the d-Stat is close to 1 there is also a good fit. According to Willmott (1982), the d-Stat is recommended for making cross-comparisons when the d-value is both relative and has bounded measures (Eq. 3.2). The lower the RMSE the better the fit between the variables (Eq. 3.5).

$$r^2 = 1 - \frac{\sum_i (O_i - P_i)^2}{\sum_i (O_i - \bar{O})^2} \qquad \text{Eq. 3.1}$$

where,

O_i is the observed value for the i measurement,

P_i is the predicted value for the i measurement, and

$\bar{O}$ is the mean of all the observed values

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|\acute{P_i}| - |\acute{O_i}|)^2} \qquad \text{Eq. 3.2}$$

where,

n is the number of observations,

$$\acute{P_i} = P_i - \bar{O}, \text{ and} \qquad \text{Eq. 3.3}$$

$$\acute{O_i} = O_i - \bar{O} \qquad \text{Eq. 3.4}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad \text{Eq. 3.5}$$

Results

Although each replication was simulated separately, the cultivar, tillage, planting and harvest dates, and meteorological and irrigation data, were the same. Differences between the replications refer to the soil profile and plant densities. Due to crop rotation between the years, the location of the replications was different. For that reason, the replication ID was used for the analysis of the results. Table 3.6 shows the location of each plot per growing season for each replication.

Table 3.6 Plots planted with maize during each growing season.

Treatment	**Replications**	**Growing seasons**	
		2016 & 2018	**2017**
C_E	Plot3	W201	W202
	Plot4	W204	W203
	Plot5	W205	W206
	Plot9	E101	E102
	Plot10	E104	E103
	Plot14	E301	E302
	Plot15	E304	E303
	Plot16	E305	E306
C_G	Plot1	W101	W102

Treatment	Replications	Growing seasons	
		2016 & 2018	2017
	Plot2	W104	W103
	Plot6	W302	W301
	Plot7	W303	W304
	Plot8	W306	W305
	Plot11	E201	E202
	Plot12	E204	E203
	Plot13	E205	E206

Calibration and evaluation of cultivar coefficients

Observed and simulated data of leaf number, leaf weight, vegetative N concentration, and yield of 2018 growing season were compared for calibrating the cultivar coefficients. The observed and simulated data of the 2016 and 2017 growing seasons were used for the evaluation of the model. However, the leaf weight and vegetative N concentration data were not collected during the 2016 growing season. The calibrated cultivar coefficients are presented in Table 3.7. P1, G3 and PHINT were lower than the initial values, while the P5 and G2 were greater. The fit between simulated and observed data for leaf number, leaf weight, vegetative N concentration and maize yield after the calibration and evaluation of the model are shown in Figures 3.4 to 3.7.

Table 3.7. Calibrated values for the cultivar coefficients for DSSAT CERES-Maize model

Cultivar coefficients	Final values
P1	206.30
P2	0.75
P5	989.30
G2	990.00
G3	8.80
PHINT	38.90

Leaf number

Figure 3.4 presents the fit between simulated and observed data for leaf number. There are sixteen lines in each graph, representing the simulated outcome from each one of the sixteen maize plots, but because simulated leaf number is not affected by fertility or planting density, there is only one common simulated line per season, while, the observed leaf number overlaps each other somewhat. The maximum simulated and observed leaf number in all seasons went up to 20 leaves. Figure 3.4 shows a good fit between simulated and observed data. The r^2 and the d-stat were close to 1 during each growing season (Table 3.8), which also indicated a good agreement between simulated and observed data. The statistics are different per plot because the observed data are different per plot. The leaf number shows a successful calibration and evaluation.

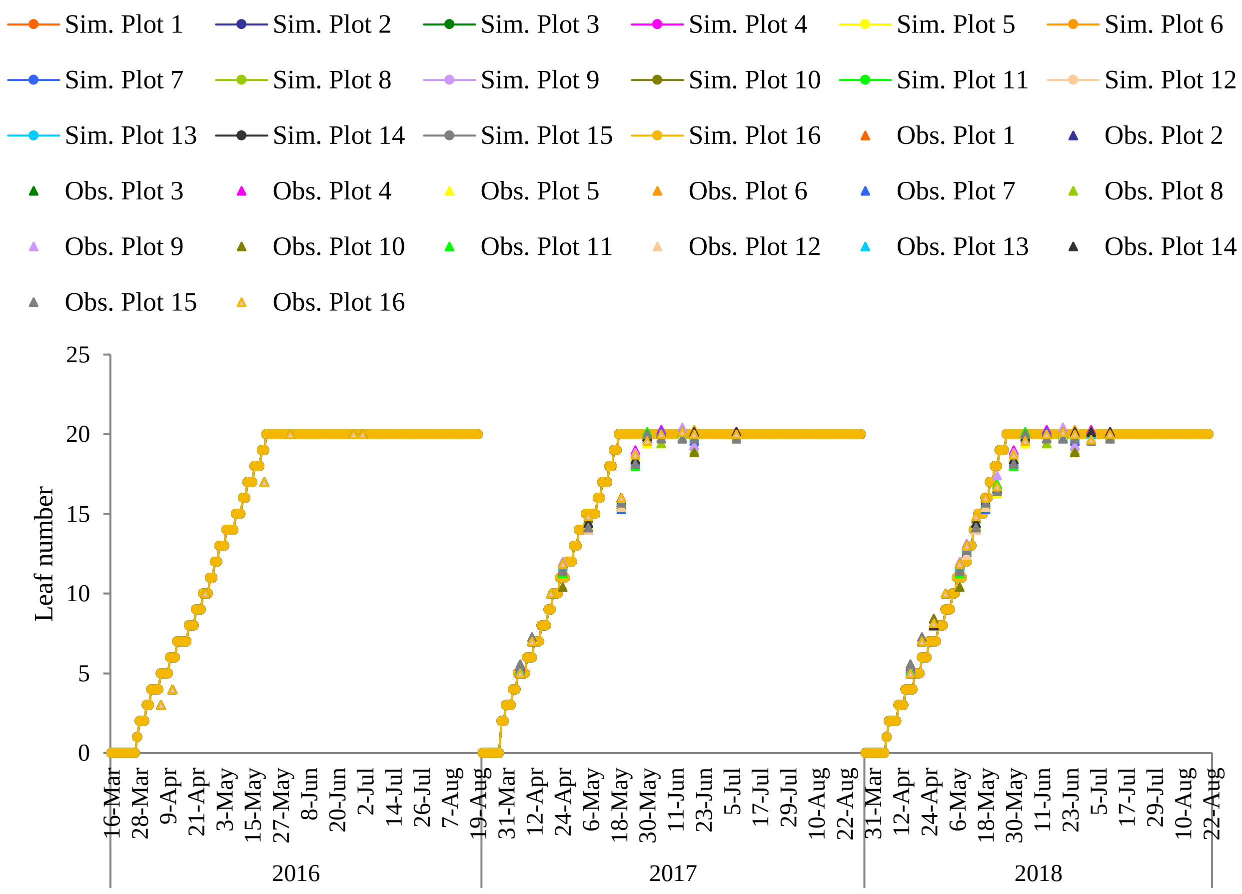


Figure 3.4 Fit between simulated and observed data for leaf number after calibration, based on 2018 data, and evaluation of the model, based on 2016 and 2017 data.

Table 3.8 Statistical indices for leaf number per replication of C_E and C_G treatment during the 2016, 2017 and 2018 growing seasons.

Treatment	**Replication**	**r^2**			**d-stat**			**RMSE**		
		2016	**2017**	**2018**	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**
C_E	Plot3	0.987	0.951	0.991	0.991	0.985	0.995	1.309	1.370	0.773
	Plot4	0.987	0.955	0.991	0.991	0.986	0.994	1.309	1.313	0.849
	Plot5	0.987	0.951	0.988	0.991	0.982	0.993	1.309	1.448	0.910
	Plot9	0.987	0.948	0.992	0.991	0.983	0.993	1.309	1.408	0.866
	Plot10	0.987	0.946	0.984	0.991	0.981	0.992	1.309	1.499	0.931
	Plot14	0.987	0.952	0.989	0.991	0.985	0.994	1.309	1.343	0.812
	Plot15	0.987	0.950	0.989	0.991	0.981	0.992	1.309	1.475	0.925
	Plot16	0.987	0.955	0.991	0.991	0.986	0.994	1.309	1.311	0.806
C_G	Plot1	0.987	0.956	0.991	0.991	0.986	0.995	1.309	1.311	0.750
	Plot2	0.987	0.956	0.992	0.991	0.985	0.995	1.309	1.349	0.780

Treatment	**Replication**	**r^2**			**d-stat**			**RMSE**		
		2016	**2017**	**2018**	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**
	Plot6	0.987	0.946	0.989	0.991	0.983	0.995	1.309	1.438	0.775
	Plot7	0.987	0.942	0.990	0.991	0.980	0.994	1.309	1.549	0.831
	Plot8	0.987	0.948	0.990	0.991	0.980	0.993	1.309	1.524	0.886
	Plot11	0.987	0.941	0.988	0.991	0.981	0.994	1.309	1.513	0.821
	Plot12	0.987	0.943	0.990	0.991	0.980	0.994	1.309	1.536	0.838
	Plot13	0.987	0.948	0.988	0.991	0.983	0.994	1.309	1.438	0.844

Leaf weight

The leaf weight (kg ha^{-1}) of the maize plants is presented in Figure 3.5. As expected, the observed weight of the leaves increased up to a maximum point and after that it decreased since the plants were senescing, something that the model depicts only partially. The model allows leaf area to decline during grain fill, but leaf weight does not decline because dead leaves remain in the leaf weight pool in the model. The simulated values follow similar trend with the experimental data for both 2017 and 2018 growing seasons. This shows that the calibration and evaluation processes were successful. The good fit between observed and simulated data is also shown by the statistical indices in Table 3.9. Both r^2 and d-stat values were greater than 0.8. The differences in statistics between the replications occur because the observed data are different between the plots.

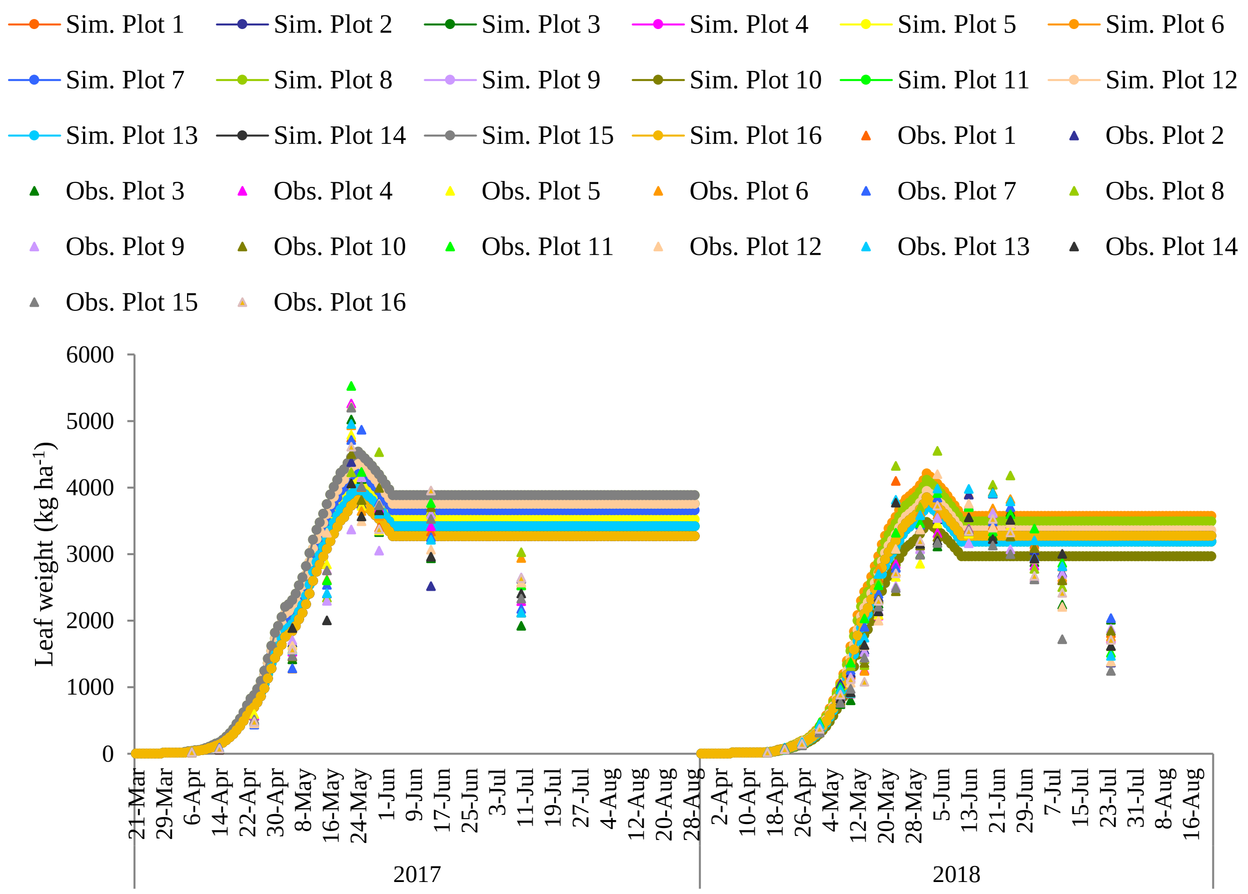


Figure 3.5 Fit between simulated and observed data for leaf weight (kg ha^{-1}) after calibration, based on 2018 data, and evaluation of the model, based on 2017 data.

Table 3.9 Statistical indices for leaf weight (kg ha^{-1}) per replication of C$_E$ and C$_G$ treatment during the 2017 and 2018 growing seasons.

Treatment	Replication	r^2		d-stat		RMSE	
		2017	2018	2017	2018	2017	2018
C$_E$	Plot3	0.853	0.907	0.944	0.960	804	526
	Plot4	0.837	0.893	0.948	0.958	666	543
	Plot5	0.905	0.875	0.968	0.949	501	597
	Plot9	0.938	0.923	0.973	0.969	483	449
	Plot10	0.909	0.896	0.973	0.972	532	420
	Plot14	0.895	0.884	0.964	0.963	494	519
	Plot15	0.859	0.840	0.940	0.920	771	731
	Plot16	0.930	0.884	0.977	0.956	475	556
C$_G$	Plot1	0.924	0.883	0.976	0.968	477	491
	Plot2	0.903	0.847	0.969	0.958	467	546

Treatment	**Replication**	**r^2**		**d-stat**		**RMSE**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**
	Plot6	0.932	0.874	0.979	0.949	464	652
	Plot7	0.872	0.926	0.956	0.981	696	372
	Plot8	0.899	0.818	0.952	0.947	676	692
	Plot11	0.849	0.890	0.947	0.971	687	459
	Plot12	0.872	0.839	0.951	0.947	674	637
	Plot13	0.858	0.858	0.955	0.959	644	571

Vegetative N concentration

The vegetative N (%), which is the concentration of N in leaves plus stems, is shown in Figure 3.6. The N concentration was greater at the beginning of the growing season and decreased with time, which the model predicted well. The success of the calibration and evaluation is also shown by the statistical indices in Table 3.10. The r^2 and d-stat have high values, while the RMSE is close to 0. As it has already been explained, the observed data were different between the plots, which explains the different values of the statistical indices between the replications.

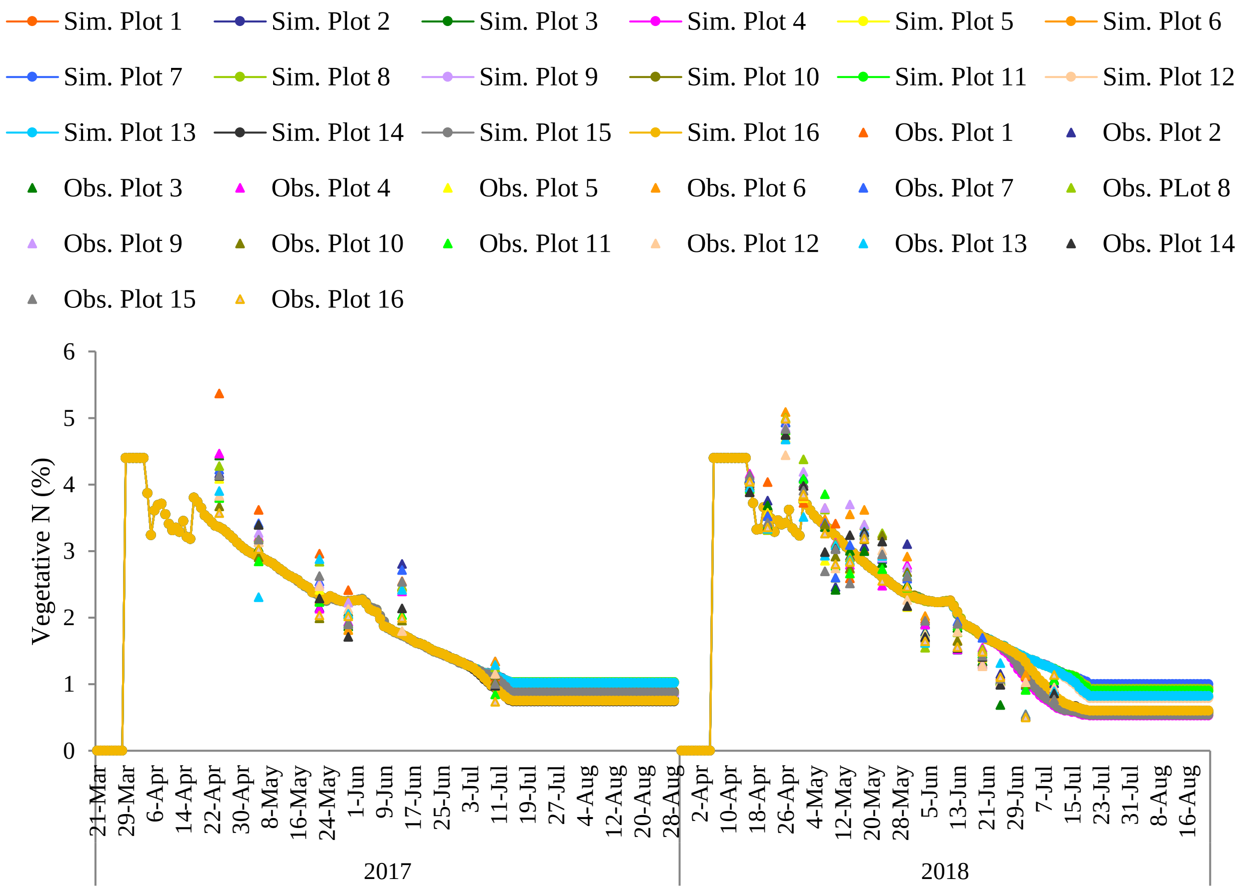


Figure 3.6. Fit between simulated and observed data for vegetative N (%) after calibration, based on 2018 data, and evaluation of the model, based on 2017 data.

Table 3.10 Statistical indices for vegetative N (%) per replication of C_E and C_G treatment during the 2017 and 2018 growing seasons.

Treatment	**Replication**	**r^2**		**d-stat**		**RMSE**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**
C_E	Plot3	0.795	0.832	0.901	0.937	0.556	0.526
	Plot4	0.833	0.882	0.904	0.959	0.557	0.423
	Plot5	0.860	0.835	0.921	0.943	0.408	0.485
	Plot9	0.922	0.843	0.948	0.934	0.372	0.543
	Plot10	0.933	0.845	0.979	0.946	0.223	0.473
	Plot14	0.876	0.852	0.937	0.939	0.453	0.516
	Plot15	0.838	0.841	0.912	0.943	0.506	0.498
	Plot16	0.950	0.825	0.982	0.932	0.224	0.536
C_G	Plot1	0.897	0.873	0.796	0.945	0.962	0.464
	Plot2	0.719	0.825	0.877	0.925	0.580	0.559

Treatment	**Replication**	**r^2**		**d-stat**		**RMSE**	
		2017	**2018**	**2017**	**2018**	**2017**	**2018**
	Plot6	0.796	0.822	0.927	0.920	0.410	0.576
	Plot7	0.831	0.853	0.883	0.936	0.581	0.505
	Plot8	0.860	0.839	0.898	0.926	0.546	0.552
	Plot11	0.921	0.866	0.969	0.941	0.286	0.485
	Plot12	0.978	0.882	0.981	0.950	0.221	0.433
	Plot13	0.669	0.843	0.888	0.935	0.501	0.497

Maize yield

The graphs in Figure 3.7 show the whole growing season from planting to harvest. The grain mass began to increase once the plants reached the reproductive stages. The yield data were collected only once, at harvesting. Thus, there is only one observed value per replication at the end of the growing seasons. The graph in Figure 3.7 shows that the simulated value of each replication fits to its observed value in the 2018 growing season, which indicates that the model predicted the final yield well after the calibration. The evaluation showed good results for both 2016 and 2017 growing seasons as well.

To perform the statistics, the simulated value of each replication was compared to the observed value of all the replications within the same treatment. The d-stat ranged from approximately 0.1 to 0.5 (Table 3.11). This occurred due to the wide range of observed yield values within the same treatment due to the different plant densities according to the stand count occurred at the end of the growing season.

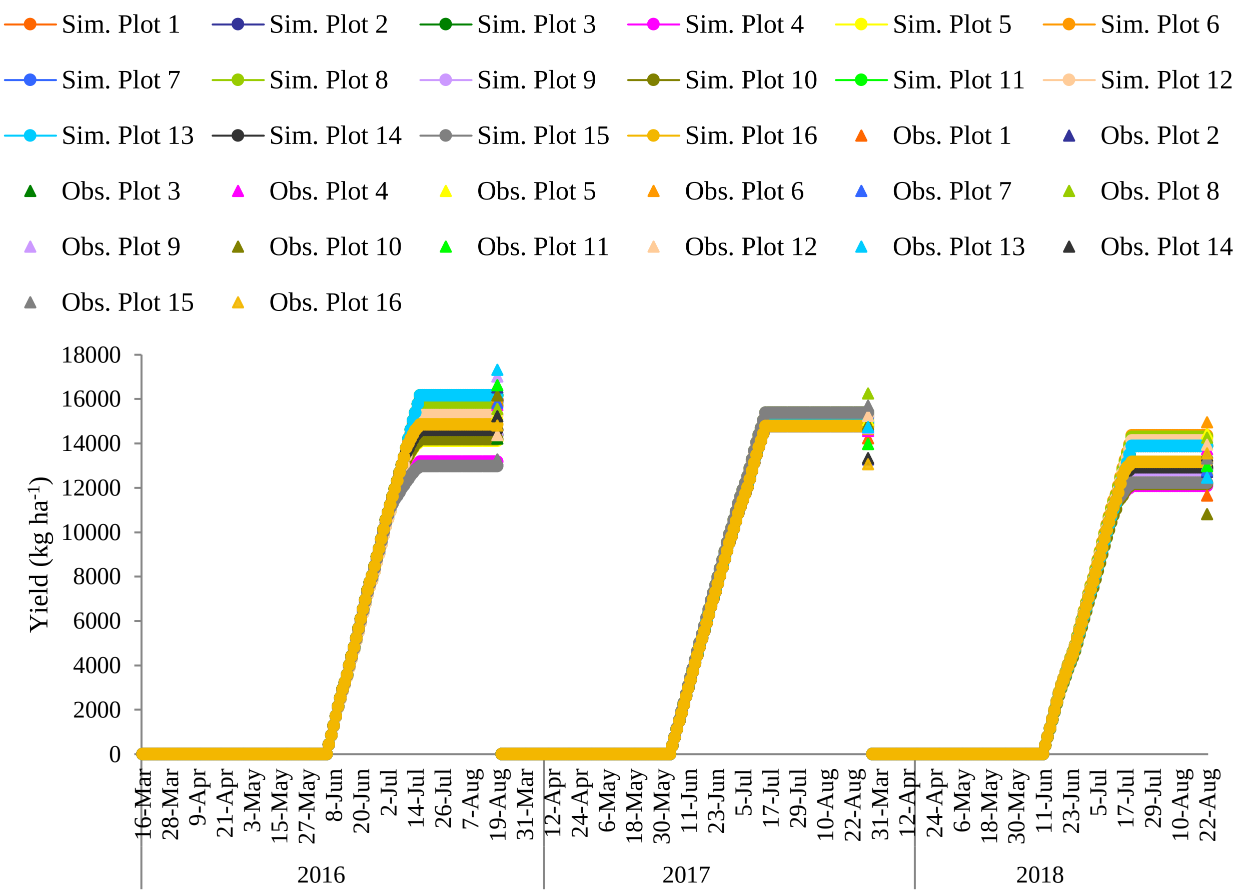


Figure 3.7 Fit between simulated and observed data for yield (kg ha^{-1}) after calibration, based on 2018 data, and evaluation of the model, based on 2016 and 2017 data.

Table 3.11 Statistical indices for maize yield (kg ha^{-1}) per replication of C_E and C_G treatment during the 2016, 2017 and 2018 growing seasons.

Treatment	**Replication**	**d-stat**			**RMSE**		
		2016	**2017**	**2018**	**2016**	**2017**	**2018**
C_E	Plot3	0.43	0.442	0.307	1370	1123	1065
	Plot4	0.391	0.389	0.398	2309	937	1528
	Plot5	0.437	0.42	0.377	1541	996	1180
	Plot9	0.429	0.389	0.336	1363	937	1095
	Plot10	0.437	0.389	0.4	1496	937	1458
	Plot14	0.401	0.297	0.277	1242	873	1044
	Plot15	0.378	0.444	0.4	2489	1192	1421
	Plot16	0.32	0.297	0.085	1139	873	998
C_G	Plot1	0.076	0.331	0.443	813	883	1208
	Plot2	0.143	0.195	0.443	817	836	1208

Treatment	**Replication**	**d-stat**			**RMSE**		
		2016	**2017**	**2018**	**2016**	**2017**	**2018**
	Plot6	0.198	0.331	0.462	823	883	1528
	Plot7	0.241	0.409	0.443	831	1000	1208
	Plot8	0.334	0.425	0.464	868	1111	1469
	Plot11	0.198	0.331	0.443	823	883	1208
	Plot12	0.43	0.418	0.463	1113	1046	1356
	Plot13	0.198	0.331	0.443	823	883	1208

A statistical analysis was performed with JMP® Pro 14.1.0 (JMP$^{®}$, Pro 14.1.0, SAS Institute Inc., Cary, NC, 1989-2019) to determine significant differences on the response variable, maize yield, between the fertilization treatments during each year of the project separately and by combining the three years of the experiment together, and between the different management practices performed each year of the project for each treatment (Table 3.12). The comparison of means was done by using Tukey–Kramer HSD test with $\alpha = 0.05$. As it was shown by Orfanou et al. (2020a), the observed yield results were similar between the C_E and C_G fertilizer treatments and no statistical differences were observed. However, the excessive amount of fertilizer in the C_G resulted in significant higher simulated yields than the C_E treatment. Similarly, to observed data, the simulated yields within the C_G treatment were significantly higher in 2016 ($p - value_{2017} = 0.0018$ and $p - value_{2018} < 0.0001$) and significantly lower in 2018 ($p - value_{2017} < 0.0001$). Although the observed data within the C_E treatment showed that the 2016 had the highest yield results but there were no significant differences during the 2017 growing season, the simulated data showed that the 2017 had a significantly higher yield than the other two growing seasons ($p - value_{2016} < 0.0001$ and $p - value_{2018} < 0.0001$). A possible explanation is that 7.6%, 70.5%, and 52.4% more N, P_2O_5 and K_2O, respectively were applied during the 2017 than the 2016 growing season. Similarly, 27.2%, 31.7% and 17.8% more N, P_2O_5 and K_2O, respectively, were applied during the 2017 than the 2018 growing season.

Table 3.12 Observed and simulated maize yield (kg ha^{-1}) results of C_E and C_G treatment during the 2016, 2017 and 2018 growing seasons. Means followed by different letters between fertilization treatments within the same growing season, between fertilization treatments, and between growing seasons within the same fertilization treatment are significantly different ($p - value < 0.05$).

Year	**Treatment**	**Observed yield* (kg ha^{-1})**	**Simulated yield (kg ha^{-1})**
By fertilization treatment			
2016	C_E	15223^a	14088^b
	C_G	16032^a	15910^a
2017	C_E	14540^a	15022^a
	C_G	14641^a	15060^a
2018	C_E	13239^a	12603^b
	C_G	13219^a	14023^a
Mean	C_E	14334^a	13904^b
	C_G	14631^a	14998^a
By growing season			
2016	C_E	15223^a	14088^b
2017		14540^{ab}	15022^a
2018		13239^b	12603^c
2016	C_G	16032^a	15910^a
2017		14641^b	15060^b
2018		13219^c	14023^c

*(Orfanou et al., 2020a)

Discussion and conclusions

The use of simulation models, such as the DSSAT CERES-Maize, has created an intensive research effort for finding ways to increase maize production. The use of models is becoming a more common approach, since they are inexpensive, detailed, and methodical for understanding the development and growth of a crop along with the soil, water, and nutrient interactions. However, due to the different conditions between fields, climate, crop varieties, etc.

the calibration and evaluation processes are crucial and necessary for obtaining results close to reality.

The focus of this study was to calibrate and validate the DSSAT CERES-Maize model for the conditions of the NESPAL field by adjusting the cultivar coefficients, which are used in DSSAT for describing the growth of a crop. The calibration of cultivar coefficients should be done when there is no stress, meaning there are no nutrient deficiencies, water or heat stress (Boote, 1999; Liu et al., 2011a). High amounts of fertilizers were applied at the beginning of each growing season and tissue samples were collected during several vegetative and reproductive stages for ensuring that there were no nutrient deficiencies. The soil moisture was monitored hourly and irrigation was applied whenever it was necessary to avoid water and heat stresses.

A new cultivar was developed by estimating the cultivar coefficients, based on phenological, growth, yield, and weather data collected throughout the growing seasons. According to Archontoulis et al. (2014), the most crucial part of calibrating a model is the prediction of maize phenology. The six cultivar coefficients (P1, P2, P5, G1, G2 and PHINT) were adjusted in a range of values based on Bao et al. (2017). Their work was used as an example, because they calibrated the CERES-Maize model by using data from variety trials which conducted in many different areas including Tifton, GA. The cultivar coefficients were calibrated by observing the fit between observed and simulated values for each one of the variables of leaf number per stem and weight, vegetative N concentration and yield of the 2018 growing season. In addition to these six coefficients, other scientists have also used the radiation use efficiency (RUE), growing degree days for emergence (GDDE), N stress coefficient, and soil fertility factor (SLPF) for simulating aboveground biomass, yield and N uptake (Liu et al., 2012).

The statistical indices of r^2, d-stat and RMSE were calculated during the calibration and evaluation processes. O'Neal et al. (2002) calibrated DSSAT CERES-Maize by minimizing the sum of absolute error of either timing or yield for specific years of their project by following the process described in the DSSAT manual (Boote, 1999). The results for all the variables showed high values of r^2 and d-stat, close to 1. Both coefficients provide a measure of accuracy for showing whether the calibration is successful. However, it should be kept in mind that statistical methods should not be used as deterministic but as descriptive tools. This was proven by Harrison (1990) and Mitchell (1997). In their studies, it was shown that regression of predicted versus experimental yield data could possibly lead to invalid conclusions. For this reason, graphs of the variables were created for giving a deeper understanding to the reader.

The leaf number of maize plants was the first variable that was tested. The results showed that the calibration and evaluation processes were successful. Maize is considered as a short-day plant since it is affected by photoperiod in a way that it develops more quickly when exposed to shorter days. As it was shown by Ritchie and Nesmith (1991), maize leaf number can be affected significantly by photoperiod and temperature. For this reason, for simulating the leaf number variable, special attention was given at the calibration of P1, P2, P5 and PHINT cultivar coefficients. A similar approach was also followed by Lizaso et al. (2003) who calibrated the values of P1, P2 and PHINT for running an accurate simulation regarding crop phenology and leaf number.

Leaf weight results showed that the built-in partitioning processes in DSSAT CERES-Maize are robust. Even if there were periods that the model over or under predicted the actual weights, it was clear that the model followed the right pattern. Similar results were found by Jagtap et al. (1993) who showed that the prediction of the model for leaf weight and other variables was within 10% of the experimental data. Furthermore, the results by Adnan et al. (2017) for the leaf dry weights along with other variables showed that the model predicts with high accuracy.

There was a good correlation between the simulated and observed data for the variable of vegetative N (%). As with the leaf weight there were periods during the growing seasons that the model either over or under predicted the actual values but again the simulated pattern was correct. Mixed results were found by Liu et al. (2011a) for a 2-year data set in which the first year the model under predicted the actual values while in the second year the simulated and experimental values were closer.

According to Pantazi et al. (2016) the improvement of crop management is highly dependent on the yield prediction concept of models. As it was presented in the results and graphs, there was a good fit between the simulated and the observed yield data, for both calibration and evaluation processes. Other studies have shown good maize yield result correlations too. For instance, a long term study that took place in nine states showed that the model can predict relatively well the yield for most locations under rainfed conditions (Kiniry et al., 1997). The yield data were collected only once, at harvest, and the single point of observed data was not enough to perform statistics. For that reason, the simulated data of each replication was compared to the observed data of all the replications within the same treatment. This resulted in $d - stat < 0.5$. Kovács et al. (1995) showed that the r^2 value was 0.82, for a 20-year experiment that took place in Hungarian conditions. In a study by Bao et al. (2017), the difference between predicted and experimental data, regarding grain yield, was not more than 3% and 8% for the calibration and evaluation process respectively.

In conclusion, DSSAT CERES-Maize model was used successfully for calibrating the cultivar coefficients, which were adjusted to achieve a good fit between simulated and observed values of leaf number per stem, leaf weight, vegetative N concentration and grain yield. The successful calibration was confirmed with the evaluation results. In both calibration and evaluation processes, the r^2 and d-stat had values close to 1. The calibrated model can be used as a DSS for identifying the influence of different management practices on the maize production. Knowing possible limitations to yield can lead to adjustments of management practices which can decrease losses, increase profitability, and have positive effects on the environment.

CHAPTER 4

SIMULATING THE EFFECT OF MANAGEMENT PRACTICES ON MAIZE YIELD[3]

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[3] Orfanou, A., D. Pavlou, G. Vellidis, K.J. Boote, and W.M. Porter. To be submitted to *Computers and Electronics in Agriculture*.

Abstract

The decision-making process of crop management is complex. Before and during the growing season, factors such as weather and soil conditions, and plant characteristics should be taken into consideration for proper management decisions. Tools, such as simulation models, can be beneficial since they can be used for analyzing data and providing possible outcomes. In this study, DSSAT CERES-Maize model was used for evaluating maize yield response to several management practices including planting date and depth, row spacing, plant density, N fertilizer rates, number and timing of side-dress N applications, and irrigation method. The predicted yields of all these scenarios were compared to the actual management practices followed during the 2016, 2017 and 2018 seasons in a field study in Tifton, GA. The optimum planting date varied from year to year due to the differences in meteorological conditions. Lower yield results would have been produced at 7 and 8 cm planting depths compared to 4, 5 and 6 cm. Narrower row spacing had better yield results, with 50 cm producing up to 3.3% higher yield than 91 cm row spacing. Plant densities of 120K plants ha^{-1} resulted in higher yields compared to 70K, 80K, 90K, 100K, 110K and 130K plants ha^{-1}. The model predicted that the higher the fertilizer rate, greater yield can be achieved, but the efficiency decreases. Splitting the N application side-dress into multiple applications could result in higher maize yields, especially in the C_E plots. Higher maize yield was produced using a sensor-based method for irrigation scheduling, compared to the UGA Extension Checkbook method and rainfed, as indicated by the model.

Introduction

Maize is an important cereal grain which is used worldwide as a staple food, livestock feed, bioethanol, sweeteners, and other industrial products. The USA is the largest maize producer in the world (USDA, 2018), which makes its production a constant pursuit of achieving higher yields. The first maize yield estimates were published by USDA in 1866 and they averaged about 1600 kg ha^{-1}. These yield results remained stagnant until the late 1930's when hybrid maize was adopted by American growers. As a result, average yields were increased to 2500 kg ha^{-1}. The improvements in genetics, mechanization of agriculture, use of pesticides, and adoption of nitrogen (N) fertilizer resulted in an annual maize yield increase rate of about 119 kg ha^{-1} since the mid-1950's. Today, the average maize yield is approximately 11100 kg ha^{-1} in the USA (USDA-NASS, 2018), while the highest national maize yield was set in Charles City, VA, at 37660 kg ha^{-1} in 2019. The second highest yield was produced in Valdosta, GA, and it was approximately 34520 kg ha^{-1} (NCGA, 2020). To maximize yields, it is important to take into consideration the interactions of plants, soil, and meteorological conditions for adjusting the management practices to improve the growth and development of maize.

Agronomic decisions in maize production

Planting date, depth, row spacing and plant density, are critical factors that can influence maize yields. There is a window of optimum planting dates for achieving maximum yields, which varies between years due to weather conditions. Soil temperature at seeding depth is a determining factor for deciding the planting date. This temperature should be above 13 ^{o}C followed by at least five warm days. These conditions normally occur during early March in Georgia (Curry, 2014). If maize is planted early, there is a risk of frost, which can affect maize stands and subsequently yield. Furthermore, yields are negatively affected if planting is delayed. In this case, yield loss can reach up to 150 kg ha^{-1} day^{-1} (Curry, 2014). Planting maize seeds at depths of 4 to 5 cm can provide adequate moisture conditions and good seed-soil contact (Lee, 2019). This can lead to uniform emergence, which can have a positive impact on maize yield. The average plant density in the US corn belt used to be 30000 plants ha^{-1} in 1930 (Duvick, 2005a), while currently it has increased to 80000 plants ha^{-1} (Li et al., 2015). High plant densities have the advantage of increasing the interception of solar radiation which can result in higher maize yields. Additionally, when maize is irrigated, high densities can increase yield potential. Row spacing is an important factor for optimizing maize yield and is correlated to plant density. Planting maize in wide rows, 95 to 100 cm, creates in-row competition for water and nutrients because there is less space between the plants. For that reason, planting in narrower rows or twin-rows has the potential of increasing maize yields. According to Brown et al. (1970), row spacing of 51 cm had higher yield compared to 102 cm in a study conducted in Georgia. A study in eastern Nebraska showed that the yield was increased by 4% by reducing the row spacing from 76 cm to 51 cm (Shapiro and Wortmann, 2006). A common approach in Georgia is to set the planter at 91 cm row spacing.

In modern agriculture, fertilizer application is a very important management practice before and during the growing season. Soil fertility varies from field to field and fertilizers are used to ensure that nutrients in the soil are at adequate levels for producing high yield results. For that reason, proper decisions regarding rates, splits and timing of fertilizer applications can provide economic and environmental benefits. N is the most important element for increasing maize productivity (Kara, 2006). N fertilizers come in the forms of nitrate (NO_3^-), ammonia (NH_3), ammonium (NH_4^+) or urea (CH_4N_2O). The temperature and availability of water during a growing season interact with N rates and influence maize yield. When N levels are low, final yield is reduced because crop growth, number of kernels m^{-2} (Uhart and Andrade, 1995) and kernels per ear (Evans et al., 2003) are reduced. Studies have shown that kernel weight can be increased when the rate of N application is increased (Moser et al., 2006; Roth et al., 2013). Moreover, according to Moser et al. (2006), N application can increase the number of kernels per row. However, the increase in fertilizer applied compared to final yield results is disproportional (Vitousek et al., 2009). In fact, according to Raun et al. (2002), the world N use efficiency in cereal grain production is at 33%, while according to Cassman et al. (2002) the fertilizer uptake efficiency is at 37% in North and central USA for maize production.

Maize sensitivity to both water stress and excessive water, makes water management a significant factor in maize production. Even if the average annual precipitation is 1300 mm in the Southeastern states, maize yield can be reduced due to inconsistent weather patterns (Lamb et al., 2011). Optimizing water availability via irrigation, especially during the flowering phase, can have a significant impact on final yields. In 2012, approximately 25% of total irrigated land in the USA was used for maize production (USDA, 2019). In Georgia, 77% of the maize crop is irrigated. A common method for scheduling irrigation in Georgia is the UGA Extension Checkbook method. This method is based on historical evapotranspiration (ET) data, which can lead to under or over irrigation. Another irrigation method that can be used is the installation of soil moisture sensors at different depths. Daily soil moisture readings in correlation to the stage of the plants can help in making proper irrigation decisions (Orfanou et al., 2019). Proper irrigation decisions can maximize maize yield potential since water stress can be reduced while irrigation assists plants with the uptake and utilization of fertilizer. Irrigation can be correlated with plant density as well. Lower plant densities should be planted in rainfed fields or areas where less water is available (Karlen and Camp, 1985).

Mathematical simulation models

Mathematical simulation models can be used as Decision Support Systems (DSS) before and during the growing seasons, since they can provide insights of growth, development and predict final yields based on different factors. A model which has been widely used for simulating several crop production systems in different conditions and many places around the world is the Decision Support System for Agrotechnology Transfer (DSSAT) (IBSNAT, 1993; Jones et al., 2017). The model can be used for predicting yield, potential environmental impact of management practices such as N leaching, evapotranspiration etc. Asadi and Clemente (2003) used the DSSAT CERES-Maize model to simulate NO_3-N leaching, N uptake, maize yield and soil moisture content in an acid sulphate soil. Saddique et al. (2019) calibrated and validated CERES-Maize successfully and identified the best planting date and irrigation applications for increasing maize yield. In North Dakota, scientists compared different methods of irrigation scheduling and the effects on grain yields and total irrigation amounts applied, and one of the methods which was tested was irrigation scheduling via DSSAT CERES-Maize model. Their results showed that the model can be used successfully for irrigation purposes since there were reductions in applied irrigation but without significant reduction in yield results (Steele et al., 1994).

Goals and objectives

The objective of this study was to use the DSSAT CERES-Maize model to evaluate the maize yield results of the actual management practices followed during a three-year field study and then comparing those outcomes to multiple hypothetical simulated management scenarios. The management practices that were simulated were planting dates, depths, plant densities, row spacing, N fertilizer rates, number and timing of N side-dress applications, and irrigation methods.

Materials and methods

In this work, the DSSAT CERES-Maize model calibrated and validated by Orfanou et al. (2020b) was used for evaluating the yield results of management practices followed during a three-year field study conducted by Orfanou et al. (2020a). The model was calibrated and validated based on the observed data collected during that period. Multiple scenarios regarding planting date and depth, row spacing, plant density, N fertilizer rates, number and timing of N side-dress applications and irrigation method were compared to the actual management practices.

Field study description

The field study conducted by Orfanou et al. (2020a) was focused on measuring the agronomic response of maize to high yield management practices during 2016, 2017, and 2018 growing seasons. The study took place in a field (Figure 4.1) located at the University of Georgia Tifton campus (31° 28.736'N, 83° 31.916'W). The climate of Tifton-Vidalia Upland portion of the Gulf-Atlantic Coastal Plain is humid subtropical. According to the University of Georgia Weather Network (UGAWN), the average annual precipitation, minimum and maximum temperatures are 1208 mm, 12.72 ^{o}C and 25.17 ^{o}C, respectively. The maize growing season lasts from March to August, which is the warmest period of the year with average temperatures ranging from 14.72 ^{o}C on March to 27.14 ^{o}C in July. These months also have the rainiest days, ranging from 7 days in April to 14 days in July, and the average total precipitation is 682 mm.

The field (Figure 4.1), which is 1.44 ha, consists of six blocks, three on the west (W1, W2, and W3) and three on the east side (E1, E2, and E3). The soil type of most of the field area is Tifton loamy sand, which is characterized as deep and well drained by NRCS Soil Survey. Additionally, the soil of half of the area of the eastern blocks (E1, E2 and E3) is an Alapaha loamy sand, which is also deep but poorly drained. Both soil types are low in natural fertility and organic matter and very strongly acid.

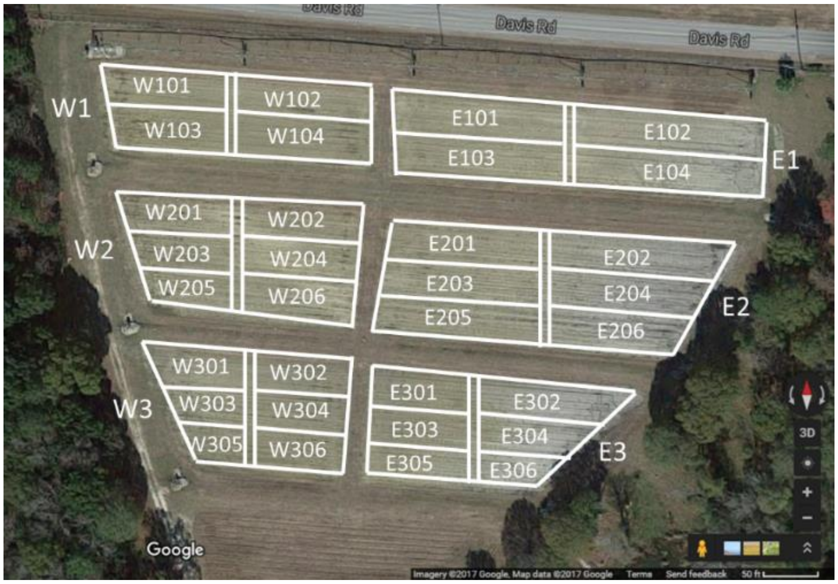
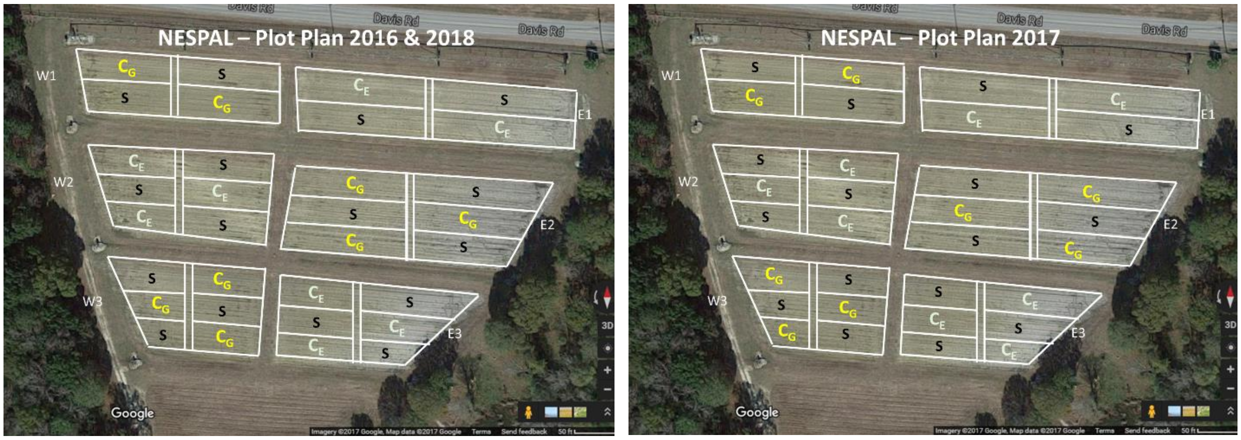


Figure 4.1 Graphical representation of the field, blocks, and plots.

For the purposes of the study, each block was separated into either four or six plots based on its size (Figure 4.1). The total number of plots was thirty-two, half of which were planted with maize (Figure 4.2), variety P1794VYHR (Pioneer, Johnston, IA, USA), and half with soybean. Before planting, the field was conventionally tilled during the 2016 growing season, while conservation tillage was applied the following two years. Planting occurred during the mid to end of March each year. The date was defined based on the soil temperature at the planting depth, which was at 5 cm. After planting, emergence data were collected, and a stand count was performed prior to harvest to know the exact plant density of each of the plots. Maize was treated with high fertilization rates (Table 4.1). One of the treatments was recommended by the UGA

Extension Service (C_E) and the other one by the Georgia Maize Growers (C_G) having a yield goal of 22 Mg ha^{-1} and 28 Mg ha^{-1}, respectively. Since the main crop of the study was maize, soybean plots were not fertilized, and they were used only for rotational purposes between the years. Furthermore, the field was irrigated based on maize requirements by a center pivot overhead irrigation system. Soil moisture readings at 07:00 AM, measured by soil moisture sensors installed in each maize plot at 0.2, 0.4 and 0.6 m depth, defined the irrigation events. Irrigation was triggered when the weighted average of the three sensors was close to 30 kPa - 35 kPa. When the moisture of the kernels was approximately 15%, maize was harvested by a two row combine. The management practices of each growing season, i.e. tillage, planting, irrigation, fertilization, were adjusted based on the weather conditions, in-field observations, data collection and previous year's final yield, and are presented in (Table 4.2).



(a) (b)

Figure 4.2 Plot plans of NESPAL field indicating the location of soybean (S) and maize (C_E and C_G fertilization treatments) plots during the (a) 2016 and 2018, and (b) 2017 growing seasons.

Table 4.1 Total fertilizer rates and application dates for C_E and C_G treatments during the 2016, 2017 and 2018 growing seasons.

Year	**Type**	**Date**	**C_E**			**C_G**		
			N ($kg\ ha^{-1}$)	**P_2O_5 ($kg\ ha^{-1}$)**	**K_2O ($kg\ ha^{-1}$)**	**N ($kg\ ha^{-1}$)**	**P_2O_5 ($kg\ ha^{-1}$)**	**K_2O ($kg\ ha^{-1}$)**
2016	Preplant	15 Mar	110	67	191	110	200	370
	At planting	16 Mar	47	45	N/A	47	45	N/A
	Side-dress	8 Apr	100	N/A	N/A	110	N/A	N/A
	Side-dress	25 Apr	100	N/A	N/A	230	N/A	N/A
	Total		**357**	**112**	**191**	**497**	**245**	**370**
2017	Preplant	15 Mar	90	146	291	90	213	404
	At planting	21 Mar	48	44	N/A	48	44	N/A
	Side-dress	13 Apr	123	N/A	N/A	123	N/A	N/A
	Side-dress	21 Apr	123	N/A	N/A	63	N/A	N/A
	Side-dress	2 May	N/A	N/A	N/A	63	N/A	N/A
	Side-dress	12 May	N/A	N/A	N/A	63	N/A	N/A
	Side-dress	26 May	N/A	N/A	N/A	63	N/A	N/A
	Side-dress	2 Jun	N/A	N/A	N/A	27	N/A	N/A
	Total		**383**	**191**	**291**	**540**	**257**	**404**
2018	Preplant	22 Mar	30	101	247	64	202	392
	At planting	28 Mar	48	44	N/A	48	44	N/A
	Side-dress	24 Apr	112	N/A	N/A	112	N/A	N/A
	Side-dress	8 May	56	N/A	N/A	56	N/A	N/A
	Side-dress	23 May	56	N/A	N/A	112	N/A	N/A
	Side-dress	5 Jun	N/A	N/A	N/A	112	N/A	N/A
	Total		**302**	**145**	**247**	**504**	**246**	**392**

Table 4.2 Management practices followed during the 2016, 2017 and 2018 growing seasons.

	2016		**2017**		**2018**	
	C_E	**C_G**	**C_E**	**C_G**	**C_E**	**C_G**
Soil core sampling						
Date	22 Feb		6 Feb		5 Feb	
Tillage						
Method	Conventional		Conservation		Conservation	
Planting						
Variety	P1794VYHR		P1794VYHR		P1794VYHR	
Planting date	16 Mar		21 Mar		28 Mar	
Planting density (seeds ha^{-1})	79000	79000	79000	79000	79000	97850
Depth (cm)	5		5		5	
Row spacing (cm)	90		90		90	

	2016		**2017**		**2018**	
	C_E	**C_G**	**C_E**	**C_G**	**C_E**	**C_G**
Planting method	Bedded		Bedded		Bedded	
Emergence date	23 Mar		26 Mar		3 Apr	
Irrigation						
SWT threshold (kPa)	<35		<35		<35	
Application rate (mm h^{-1})	71		36		36	
Total amount applied (mm)	408		235		261	
Harvest						
Harvest dates	19 Aug		29 Aug		22 Aug	

DSSAT CERES-Maize model

DSSAT is a software that simulates growth, development, and yield as a function of the soil-plant-atmosphere dynamics (Hoogenboom et al., 2015; Jones et al., 2003). The software can be used for over 42 crops. The DSSAT Version 4.6.5.0 CERES-Maize model was used in this study for evaluating the yield results of different management practices in maize production.

Meteorological, soil and plant data as well as information of the management practices followed during the field study were used for setting up the model. Daily weather including total daily solar radiation (MJ m^{2}), maximum and minimum daily air temperature (^{o}C), total daily precipitation (mm), dew point temperature (^{o}C), total daily wind speed (m s^{-1}), total daily pan evaporation (mm) and relative humidity (%) were obtained from the UGAWN. Soil core samples were collected at 0.75 m depth in each one of the plots twice per year, before planting and after harvesting the maize. The samples were separated into five segments of 0.15 m depth. The soil texture, pH, CEC (cmol kg^{-1}) and TN (%) of the samples collected in February 2018 were used for creating the modeled soil profile of each plot. Based on these data, the SBUILD program in DSSAT estimated the lower limit (LL), drain upper limit (DUL), saturated water content (SAT), bulk density (BD, g cm^{-3}), saturated hydraulic conductivity (K_s, cm h^{-1}), and root growth factor

(RGF). The type of previous crop was fallow, wheat and rye in 2016, 2017 and 2018, respectively, and were defined in the initial conditions. Information about the management practices, i.e. cultivar, planting, irrigation, fertilizer, tillage, and harvest were used as inputs into the model as well.

The cultivar was created by estimating the cultivar coefficients of P1, P2, P5, G2, G3 and PHINT (Table 4.3) based on observed phenological data throughout the three growing seasons. During the calibration process, the cultivar coefficients were adjusted to achieve a good fit between observed and simulated data of maize yield, leaf number, leaf weight and vegetative N concentration of the 2018 growing season. The observed data collected during the 2018 growing season was used for calibrating the model while the data from 2016 and 2017 seasons were used for validation. When calibration provided satisfying results, the new cultivar coefficients were used in another set of observed data, those of 2016 and 2017.

Table 4.3 Description and calibrated values of the cultivar coefficients.

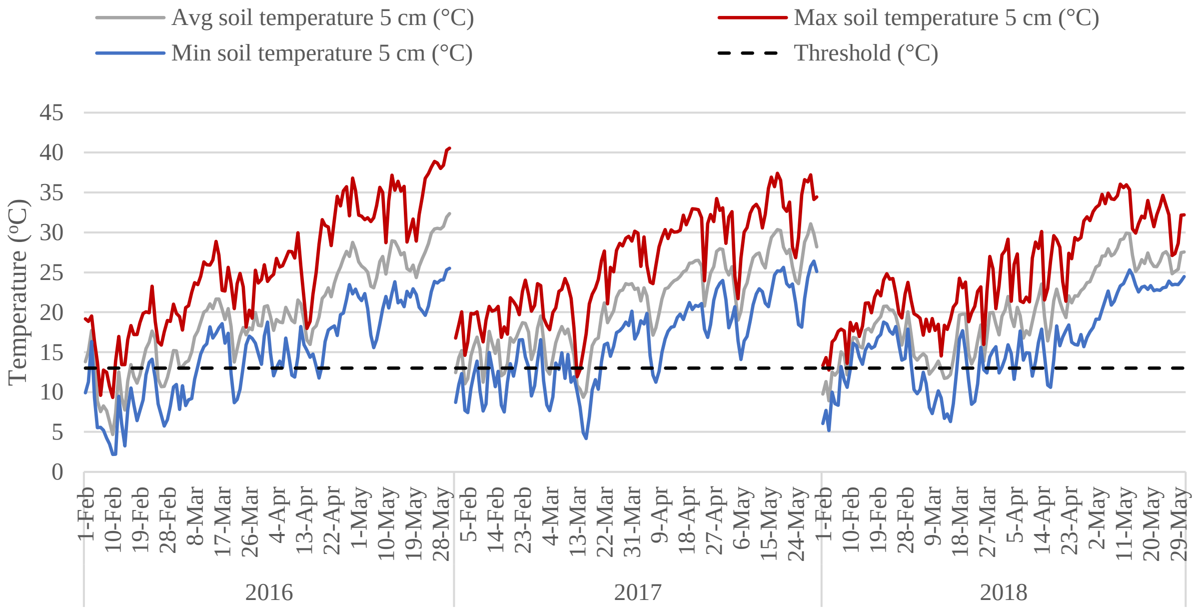
Cultivar coefficients	**Description**	**Calibrated values**
P1	Thermal time from seedling emergence to the end of the juvenile phase (GDD)	206.30
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (day/h)	0.75
P5	Thermal time from silking to physiological maturity (GDD)	989.30
G2	Maximum possible number of kernels per plant (kernels/plant)	990.00
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)	8.80
PHINT	The interval in thermal time between successive leaf tip appearances (GDD)	38.90

Agronomic management scenarios

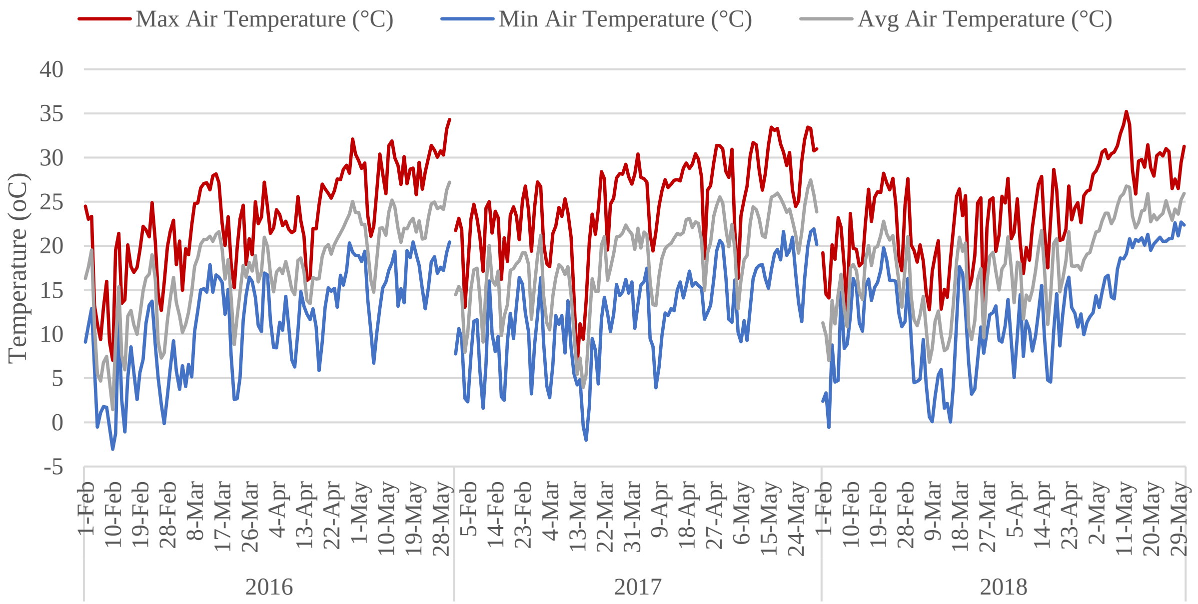
The DSSAT CERES-Maize calibrated and validated by Orfanou et al. (2020b) was used for conducting a wide range of management scenarios regarding planting date and depth, row spacing, plant density, N fertilizer rates, splits and timing of N side-dress applications, and irrigation method in an effort to assess factors that could be limiting the final maize yields of 2016 to 2018 growing seasons. Due to the differences in weather, initial conditions, and management practices between the years, the scenarios were evaluated for all the three growing seasons of the field study. Each replication of each treatment, i.e. each one of the sixteen maize plots, was simulated separately to increase model performance due to the differences in the soil profile across the field and plant densities at harvest. For all the cases, the simulation starting date was on the 1st of February each year.

Planting date

Soil temperature at planting depth, 5 cm (Figure 4.3(a)), was observed daily via UGAWN from the end of February until maize was planted in March each year. When soil temperatures remained above 13 ^{o}C, dashed line in Figure 4.3(a), for at least five consecutive days, maize was planted. The actual planting dates (Scenario 0 in Table 4.4) for all the treatments and plots were on the 16th of March 2016, 21st of March 2017 and 28th of March 2018. Seven more scenarios were evaluated in terms of yield, starting at the 15th of February up to the 15th of May with approximate fifteen day interval, i.e. Scenario 1: 15th of February, Scenario 2: 28th of February, Scenario 3: 15th of March, Scenario 4: 31st of March, Scenario 5: 15th of April, Scenario 6: 30th of April, Scenario 7: 15th of May. The harvest date was defined automatically by the model (Table 4.4). In general, the harvest date was during July when maize was planted before the 31st of March, and during August when it was planted from the 1st of April to the 15th of May. Table 4.5 shows the average temperature, total precipitation, and average solar radiation of the selected scenarios.



(a)



(b)

Figure 4.3 Daily minimum, maximum and average (a) soil temperatures at depth of 5 cm and (b) air temperatures from 1 Feb until 31 May during the 2016, 2017 and 2018 growing seasons.

Table 4.4 Simulated planting date scenarios and harvesting dates of each scenario during the 2016, 2017 and 2018 growing seasons.

Scenario	**Simulation start date**	**Growing season**					
		2016		**2017**		**2018**	
		Planting	**Harvest**	**Planting**	**Harvest**	**Planting**	**Harvest**
0	1 Feb	16 Mar	19 Aug	21 Mar	29 Aug	28 Mar	22 Aug
1		15 Feb	6 Jul	15 Feb	7 Jul	15 Feb	06 Jul
2		28 Feb	10 Jul	28 Feb	12 Jul	28 Feb	14 Jul
3		15 Mar	19 Jul	15 Mar	17 Jul	15 Mar	19 Jul
4		31 Mar	29 Jul	31 Mar	28 Jul	31 Mar	29 Jul
5		15 Apr	5 Aug	15 Apr	6 Aug	15 Apr	6 Aug
6		30 Apr	16 Aug	30 Apr	17 Aug	30 Apr	14 Aug
7		15 May	27 Aug	15 May	28 Aug	15 May	27 Aug

Table 4.5 Average temperature (^{o}C), total precipitation (mm), average solar radiation (MJ m^{-2}) during successively later sown growing seasons of the simulated scenarios.

Scenario	**Avg air temperature (^{o}C)**			**Total precipitation (mm)**			**Avg solar radiation (MJ m^{-2})**		
	2016	**2017**	**2018**	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**
0	23.32	23.83	23.66	630	495	795	20.52	19.54	18.68
1	20.37	20.61	20.39	496	345	513	19.58	18.98	17.53
2	21.33	21.25	20.87	434	373	540	20.08	19.44	18.39
3	22.40	22.26	22.14	447	363	526	20.61	19.88	18.64
4	23.61	23.39	23.32	341	416	542	21.64	19.98	19.02
5	24.65	24.13	24.35	309	351	594	21.85	19.64	19.01
6	25.50	24.75	25.48	388	395	615	21.72	19.23	19.11
7	26.23	25.59	25.82	368	362	696	21.57	18.92	18.49

Planting depth

The actual planting depth was at 5 cm during the three years of the project, Scenario 0. Four more scenarios were evaluated in DSSAT CERES-Maize at depths of 4 cm (Scenario 1), 6 cm (Scenario 2), 7 cm (Scenario 3) and 8 cm (Scenario 4).

Row spacing

During all years of the field study, the actual row spacing (Scenario 0) was at 91 cm row, which is a common approach for growers in Georgia. Five more scenarios regarding row spacing of 50 to 100 cm with 10 cm increment were evaluated, i.e. Scenario 1: 50 cm, Scenario 2: 60 cm, Scenario 3: 70 cm, Scenario 4: 80 cm, Scenario 5: 100 cm.

Plant density

In the first two years of the field study the plant density at planting was approximately 79K plants ha^{-1} for both treatments. However, it was increased to approximately 98K plants ha^{-1} only for the C_G treatment in the third year. After planting, emergence data was collected to ensure an adequate stand. A couple of days before harvesting one more stand count was done, and that plant density was the one used in the DSSAT CERES-Maize model and it was slightly different from plot to plot. Six more scenarios regarding plant density ranging from 70K (Scenario 1) to 130K plants ha^{-1} (Scenario 6) with an increment of 10K plants ha^{-1} were evaluated in terms of yield.

N fertilizer rates

During the field study, the total fertilizer rates were based on the UGA Extension Service and Georgia Maize Growers professional recommendations for C_E and C_G treatment, respectively. The rates were slightly different between the years. The average N fertilizer rate was approximately 350 kg ha^{-1} for the C_E and 500 kg ha^{-1} for the C_G treatment. The actual N fertilizer rates refer to the Scenario 0. In the other five scenarios, the N fertilizer rates were adjusted from 150 kg ha^{-1} to 650 kg ha^{-1}, with a 100 kg ha^{-1} interval. More specifically, Scenario 1: 150 kg ha^{-1}, Scenario 2: 250 kg ha^{-1}, Scenario 3: 350 kg ha^{-1}, Scenario 4: 450 kg ha^{-1}, Scenario 5: 550 kg ha^{-1}, Scenario 6: 650 kg ha^{-1}. In all the scenarios, the amount of N fertilizer at pre-plant applications was kept at the same rates as the actual inputs during the field study. The remaining

N fertilizer was split equally across the actual number of side-dress applications that were followed in each fertilizer treatment and growing season.

Number of N side-dress applications

One of the management practices that was not consistent between the growing seasons and treatments during the field study was the number of side-dress applications. In this model simulation, the effect of splitting the total side-dress N fertilizer into less or more applications on the final yield was tested. The N fertilizer rates, as well as the amount of N fertilizer at pre-plant and at planting were kept the same as the actual inputs during the growing seasons. The remaining N fertilizer was split equally between the side-dress applications. Scenario 0 referred to the actual number of side-dress applications applied during the field study, which differed between the years and treatments. There were 2 side-dress applications for both treatments in 2016, 2 for C_E and 6 for C_G in 2017, and 3 for C_E and 4 for C_G in 2018. Six more scenarios were evaluated, in which the number of side-dress applications ranged from 1 to 6, with an interval of 1, i.e. Scenario 1: 1 side-dress applications, Scenario 2: 2 side-dress applications, Scenario 3: 3 side-dress applications, Scenario 4: 4 side-dress applications and Scenario 5: 5 side-dress applications.

Timing of side-dress N applications

Five scenarios regarding the timing of applying the side-dress N fertilizer were evaluated. In all cases, the actual N fertilizer rates, and number of side-dress applications for each treatment during each growing season were used. Scenario 0 refers to the actual scenario. During the 2016 growing season, the first side-dress was applied 3 weeks after planting (WAP) and the second two-weeks later. During 2017, the first side-dress was also applied 3 WAP and then a weekly interval was followed, except for the fifth side-dress which was applied two-weeks after the previous application. During 2018, the first side-dress was applied 4 WAP and the remaining were applied with a two-week interval. In the remaining four scenarios, the timing of the first side-dress application ranged from 2 to 5 WAP, with a weekly interval, i.e. Scenario 1: 2 WAP, Scenario 2: 3 WAP, Scenario 3: 4 WAP, Scenario 4: 5 WAP. The temporal distribution of the following side-dress applications was the same as the actual.

Irrigation scenarios

The maize yield of three irrigation scheduling management scenarios of the field experiment's fertilization treatments (C_G and C_E) were evaluated using the DSSAT CERES-Maize model. Scenario 0 refers to the actual irrigation method, which was the sensor-based method, Scenario 1 refers to the UGA Extension Checkbook method, and Scenario 2 refers to the rainfed treatments. The temporal distribution of irrigation and precipitation events of each one these scenarios for each maize growing season is presented in Figure 4.4, while Table 4.6 shows the total amount of water applied.

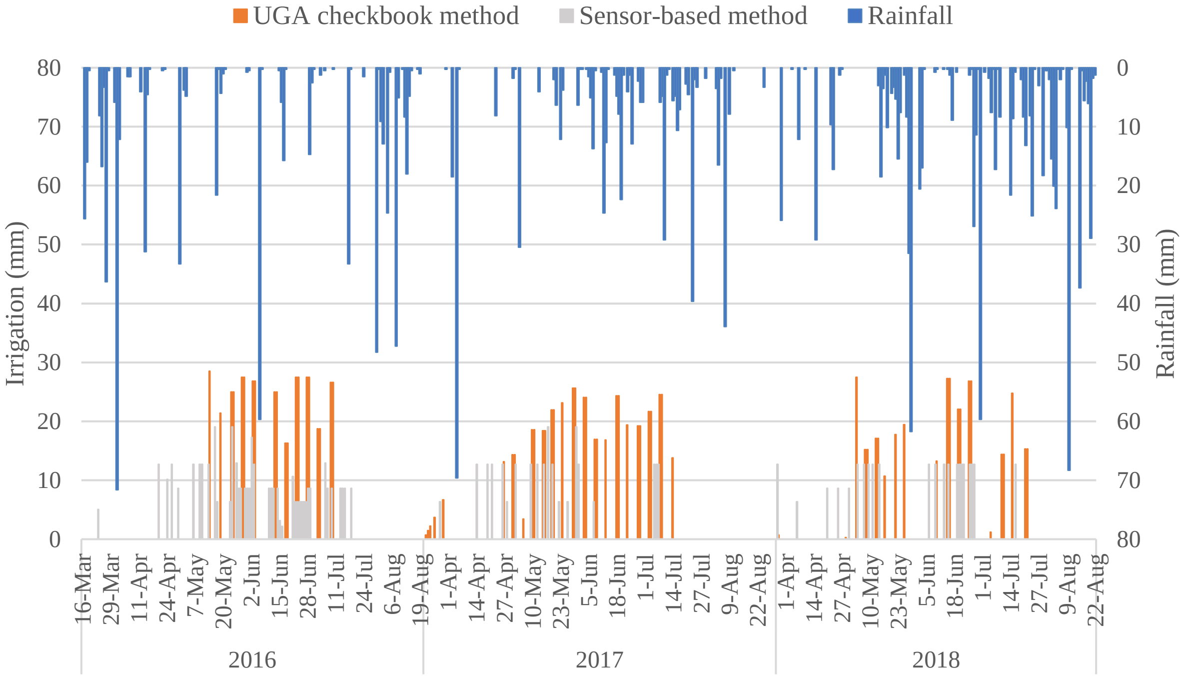


Figure 4.4 Daily amount and frequency of rainfall and irrigation based on the sensor-based and UGA Extension Checkbook method during the 2016, 2017 and 2018 growing seasons.

Table 4.6 Amount of irrigation, rainfall, and total rainfall plus irrigation based on the sensor-based and UGA Extension Checkbook method during the 2016, 2017 and 2018 maize growing seasons. The Total column indicates the sum of irrigation and precipitation.

Year	**Sensor-based**		**UGA Extension Checkbook**		**Rainfed**	
	Irrigation (mm)	**Total (mm)**	**Irrigation (mm)**	**Total (mm)**	**Irrigation (mm)**	**Total (mm)**
2016	408	1038	492	1122	0	630
2017	235	730	564	1059	0	495
2018	261	1058	392	1189	0	797

During the field study, the University of Georgia Smart Sensor Array (UGA SSA) (Vellidis et al., 2008) was used to measure soil water tension (SWT). A probe with three Watermark® (Irrometer, Riverside, California, USA) soil moisture sensors at 0.2, 0.4, and 0.6 m was installed in each maize plot. The UGA SSA also consists of an electronics package to process and transmit data. Data were collected hourly and sent wirelessly. The irrigation scheduling was based on the SWT at 07:00 AM. Eq. 4.1 was used to estimate the weighted average SWT of the three sensor depths (Orfanou et al., 2019). The SWT readings of the three sensors as well as the weighting factors α, β, and γ were applied to the Eq. 4.1. The weighting factors differed according to the phenological stage of maize (Table 4.7) and were defined based on the anticipated root depth at that stage. At the beginning of the growing season, more weight was given to the shallow sensors, while the weight was being increased and distributed to the deeper sensors as the rooting depth was lengthened (Orfanou et al., 2019). Due to the sandy soils, in which SWT increases rapidly during drying, a low weighted average SWT threshold of 30 kPa - 35 kPa was used for triggering the irrigation events. The actual irrigation events that took place during the three years of the field study were used in this scenario (Scenario 0). Figure 4.5 presents the irrigation scheduling, daily measured response of SWT per block, and irrigation frequency and rate according to the field study conducted by Orfanou et al. (2020a).

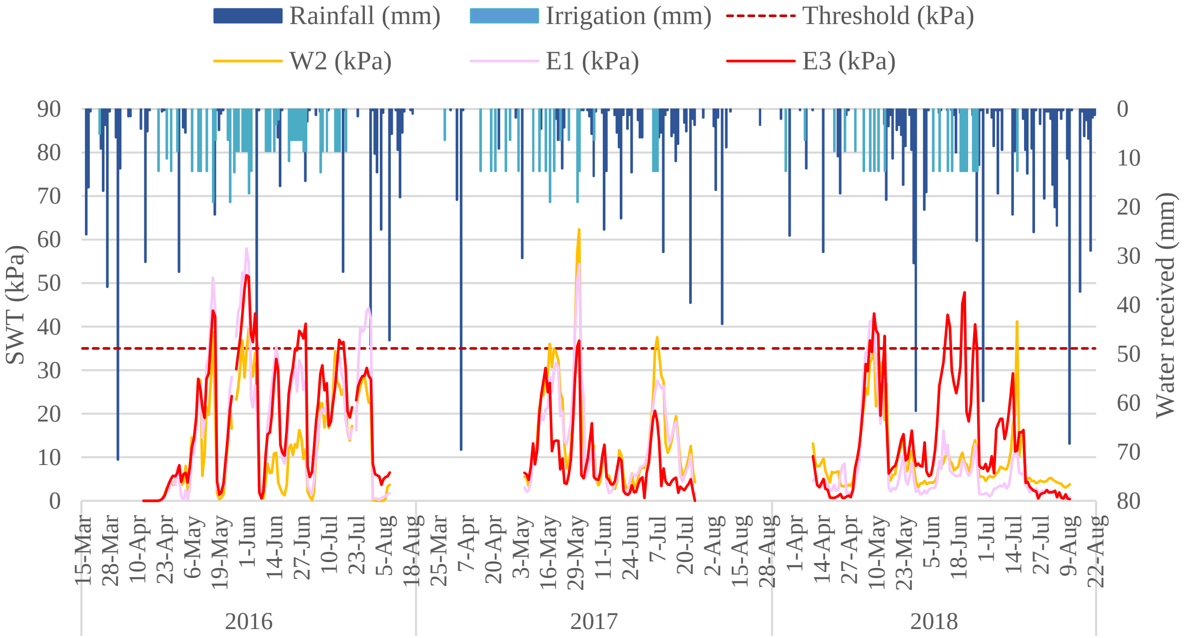
$$\text{SWT Weighted Average} = \alpha * \text{SWT}_{0.2\ \text{m}} + \beta * \text{SWT}_{0.4\ \text{m}} + \gamma * \text{SWT}_{0.6\ \text{m}} \qquad \text{Eq. 4.1}$$

where,

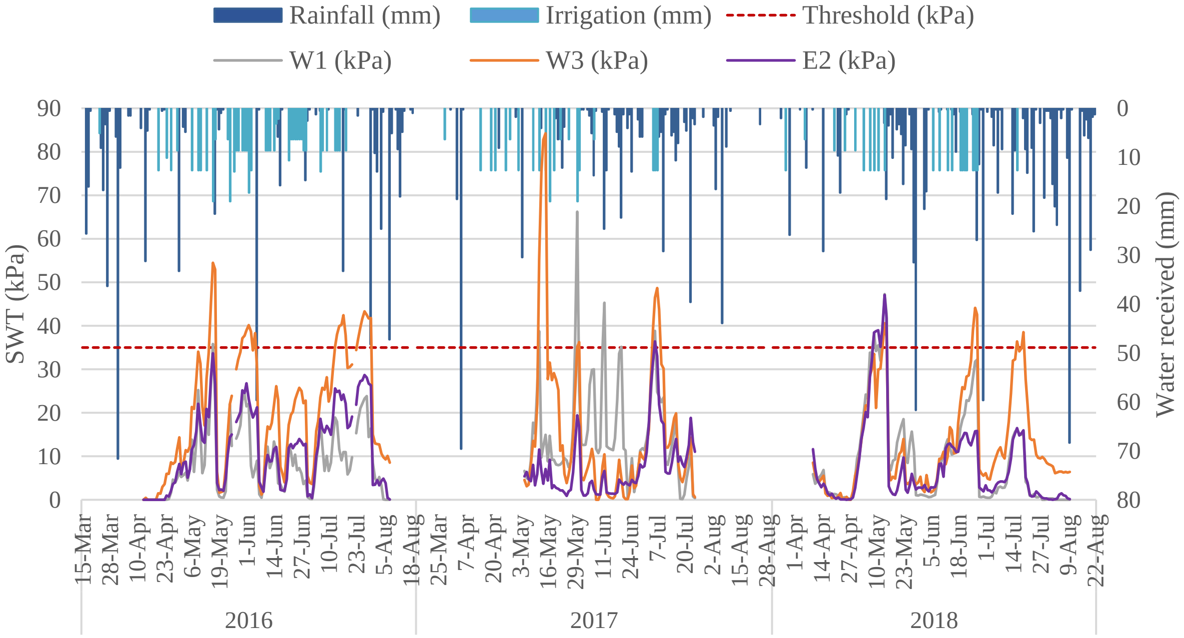
α, β and γ are the weighting factors based on the maize phenological stage (Table 4.7).

Table 4.7. Weight of each soil moisture sensor based on the GDDs and phenological stage.

GDDs (ºC)	**Stage**	**α – 0.2 m (%)**	**β – 0.4 m (%)**	**γ – 0.6 m (%)**
0-354	VE-V4	80	20	0
355-724	V5-V8	60	30	10
725-878	V9-V11	50	30	20
879-1099	V12-VT	50	25	25
1100<	R1-black layer	40	30	30



(a)



(b)

Figure 4.5 Daily average SWT and total amount of water received through applied irrigation or rainfall during the 2016, 2017 and 2018 growing seasons for (a) C_E and (b) C_G blocks.

In the Scenario 1, the irrigation scheduling was based on the UGA Extension Checkbook method, which is a historical ET calendar method, which provides the weekly water requirements of the crop. The UGA Extension Checkbook method was developed by using 30-year historical weekly evapotranspiration (ET) data from the Coastal Plain of Georgia and the FAO-56 crop coefficient (Kc) (Allen et al., 1998) values for maize. The amount of irrigation was estimated by subtracting the amount of water received via rainfall from the weekly requirements. The University of Georgia's annual Corn Production Guide (Lee, 2019), provides more information about estimating the maize water requirements based on the UGA Extension Checkbook method. According to the guidelines of the corn production in Georgia, 0.1 mm per mm of soil was used for the water holding capacity due to the Tifton loamy sand soil type of the field. The total available water was estimated based on the rooting depth. At each irrigation event, the amount of water applied was 50% of the water holding capacity. During the peak water use periods, the UGA Extension Checkbook method recommended multiple irrigation applications within a week period.

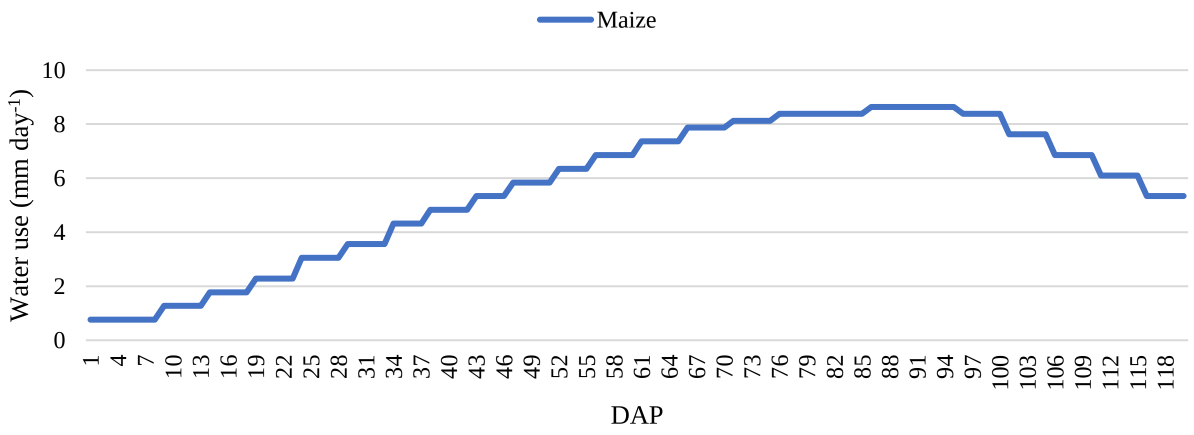


Figure 4.6 Maize weekly water use (mm day^{-1}) in Georgia according to UGA Extension Checkbook method (Lee, 2019).

In the rainfed scenario (Scenario 2), no water was applied through irrigation and the only source of water was precipitation. This scenario was used since it is a common approach for testing the response of maize to a specific irrigation scheduling method.

Results

Figures 4.7 to 4.14 show the results of each management scenario (x-axes) in terms of final maize yield, kg ha^{-1}, (y-axes). The management practices refer to planting date, planting depth, row spacing, plant density, N fertilizer rate, number and timing of N side-dress applications, and irrigation method. The x-axes also show the three maize growing seasons from 2016 to 2018 during which the simulation was conducted. The colored lines with the markers represent the sixteen maize plots.

The simulated yields (kg ha^{-1}) of the actual management practices followed by (Orfanou et al., 2020a) for each treatment in 2016, 2017 and 2018 growing seasons are presented in Tables 4.9 to 4.16. The simulated yields of the actual scenarios were used as a reference yield and compared to the simulated yields of the other scenarios. The Tables 4.9 to 4.16 also present the relative yield (%) if a different management scenario was followed according to the DSSAT CERES-Maize model.

Due to crop rotation between the years, the location of the replications was different. For that reason the replication ID in Table 4.8 was used for the analysis of the results.

Table 4.8 Maize plots of each growing season and their fertilization treatment.

Treatment	**Plots**	**Growing seasons**	
		2016 & 2018	**2017**
C_E	Plot 3	W201	W202
	Plot 4	W204	W203
	Plot 5	W205	W206
	Plot 9	E101	E102

Treatment	Plots	Growing seasons	
		2016 & 2018	**2017**
	Plot 10	E104	E103
	Plot 14	E301	E302
	Plot 15	E304	E303
	Plot 16	E305	E306
C_G	Plot 1	W101	W102
	Plot 2	W104	W103
	Plot 6	W302	W301
	Plot 7	W303	W304
	Plot 8	W306	W305
	Plot 11	E201	E202
	Plot 12	E204	E203
	Plot 13	E205	E206

Yield response to planting date

Seven planting date scenarios were simulated and the predicted yield results of each scenario according to the DSSAT CERES-Maize are presented in Figure 4.7. The dates ranged from 15th of February to 15th of May with biweekly intervals. The three seasons have a very different shapes of yield response to planting date. More specifically, the maximum simulated yield occurred at planting dates of 31st of March 2016, 15th of February and 21st of March 2017, and 30th of April 2018 for C_E treatment and 15th of March 2016, 15th of February 2017 and 30th of April 2018 for C_G treatment (Figure 4.7 and Table 4.9). The driving factors for these results were the air temperature and average solar radiation (Table 4.5) during the growing seasons since there was adequate irrigation in all the scenarios. Low temperatures, when planting early, can delay emergence, which can lead to lower yields (Yang et al., 2011b), while they can affect growth and development of plants by reducing leaf number and internode length (Tsimba et al., 2013). The 2017 season had warmer temperatures in February compared to the other two years, which had a positive effect on the yields.

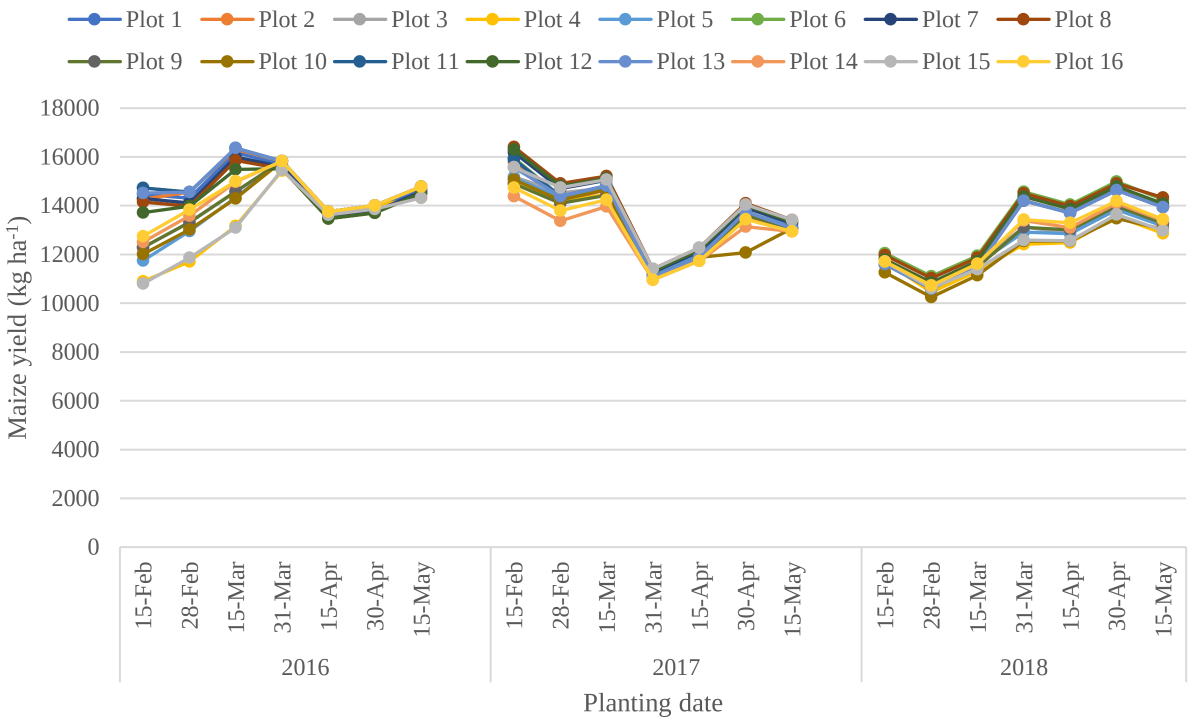


Figure 4.7 Modeled yield predictions of planting date scenarios from 15 Feb to 15 May for all the plots during the 2016, 2017 and 2018 growing seasons.

Table 4.9 shows how the model predicted that the yield would have been changed if the planting date was shifted compared to the actual scenario. Planting on the 15th of March 2016 would have resulted to 1.2% and 1.3% higher yields for C_E and C_G treatment respectively compared to the actual planting date (16th of March 2016), while the yield would have been increased by 11.7% for C_E and decreased by 1.3% for C_G if the planting date was shifted to the 31st of March 2016. A planting date on the 15th of February 2017 would have provided higher yields by 6.3% for the C_G treatment compared to the actual planting date (21st of March 2017). An increase of 9.9% for C_E and 5.1% for C_G treatment could have been achieved if the maize was planted on the 30th of April 2018 compared to the actual planting date (28th of March 2018).

However, in DSSAT CERES-Maize model, the grain number is set by the solar radiation during about a nine day period, P4 phase, before grain grown begins, which shifts when the planting date is shifted, which explains the bounce planting date effects in the results.

Table 4.9 Average simulated maize yields (kg ha^{-1}) for the actual planting date scenario (16 Mar 2016, 21 Mar 2017, 28 Mar 2018), and relative yield (%) compared to the planting date scenarios of 15 Feb, 28 Feb, 15 Mar, 31 Mar, 15 Apr, 30 Apr and 15 May for each growing season and treatment.

		Planting date							
Trt	**Year**	**Actual date**	**15 Feb**	**28 Feb**	**15 Mar**	**31 Mar**	**15 Apr**	**30 Apr**	**15 May**
		Yield (kg ha^{-1})	**Relative yield (%)**						
C_E	2016	14088	84.5	91.9	101.2	111.7	97.5	99.3	104.1
	2017	15022	99.8	94.2	96.8	74.1	79.5	89.5	87.4
	2018	12603	92.3	84.1	91	102.7	101.9	109.9	104.6
C_G	2016	15910	90.2	90	101.3	98.7	85.7	87.3	92.2
	2017	15060	106.3	96.4	99	74.1	79.5	91.9	87.4
	2018	14023	83.6	76.6	82.9	102	98.5	105.1	100.2

Yield response to planting depth

The maize yield response to five scenarios of planting depth, including the actual planted depth (5 cm), was evaluated in DSSAT CERES-Maize. The simulation scenarios referred to depths from 4 to 8 cm with 1 cm increment. It should be noticed that the same plots were used for the 2016 and 2018 growing seasons but differed in 2017 due to rotation (Table 4.8). All the plots of the 2017 season had better yield results at the 4 cm planting depth by 3% for C_E and 0.3% for C_G compared to the actual planting depth. Adequate soil moisture and warmer temperatures assisted with germination without causing uniformity issues. Better yield results were simulated when maize was planted at the 4 or 5 cm depth during the 2016 growing season. However, in 2018, the same plots showed higher yields by 2.3% for C_E and 4.7% for C_G when they were planted at the 6 cm depth compared to the 5 cm depth. This have caused different emergence dates and therefore created a different time for the decision on grain number, i.e. different solar radiation in P4 phase.

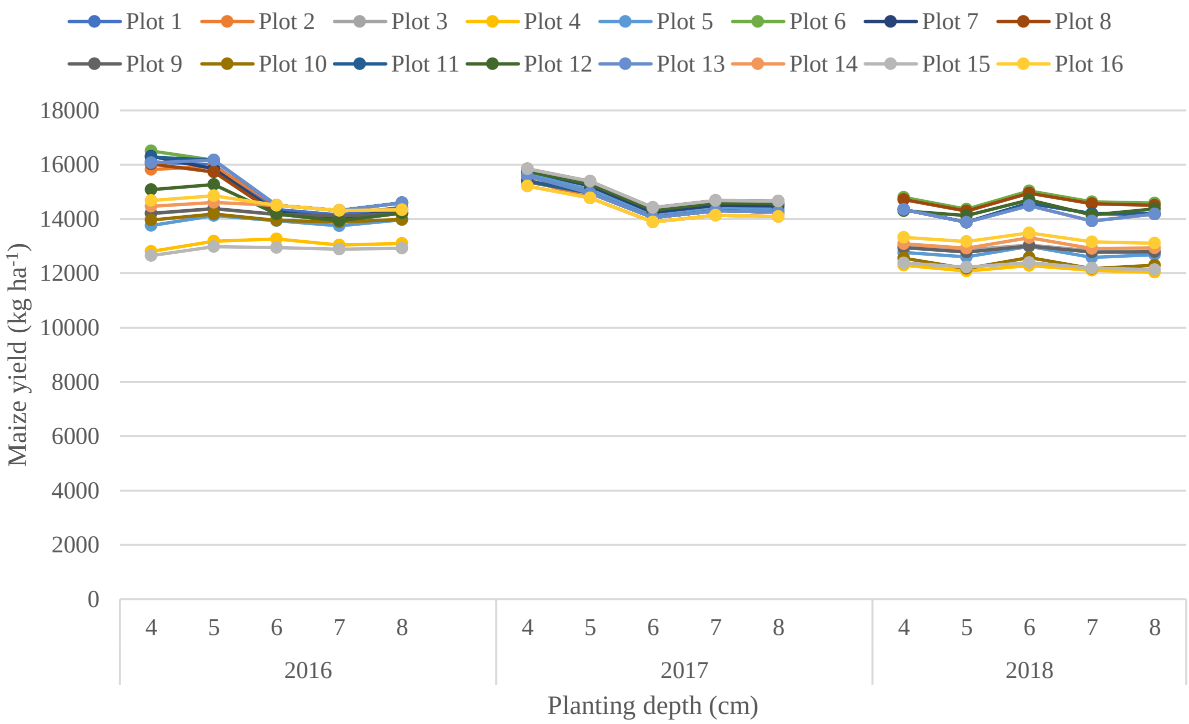


Figure 4.8 Modeled yield predictions of planting depth scenarios from 4 to 8 cm for all the plots during the 2016, 2017 and 2018 growing seasons.

Table 4.10 Average simulated maize yields (kg ha^{-1}) for the actual planting depth scenario (5 cm), and relative yield (%) compared to the planting depth scenarios of 4, 5, 6, 7 and 8 cm for each growing season and treatment.

Planting depth (cm)							
Trt	**Year**	**Actual planting depth**	**4**	**5**	**6**	**7**	**8**
		Yield (kg ha^{-1})	**Relative yield (%)**				
C$_E$	2016	14088	98.3	100	98.9	98	98.5
	2017	15022	103	100	93.9	95.6	95.3
	2018	12603	101.5	100	102.3	99.9	99.9
C$_G$	2016	15910	100.4	100	90.2	88.9	90.7
	2017	15060	100.3	100	93.9	95.5	95.3
	2018	14023	103	100	104.7	101.4	101.9

Yield response to row spacing

Six scenarios of row spacing, from 50 to 100 cm with 10 cm interval, were evaluated. The model indicated a negative linear relationship between row spacing and maize yield, i.e. lower maize yields were predicted in wider row spacing, regardless of the growing season, fertilizer treatment, and plot. Narrower rows provide more space between plants on the same row, which reduces interplant competition for light, water, and nutrients. As the row spacing is decreased, the canopy light extinction coefficient is increased, which results to higher yields.

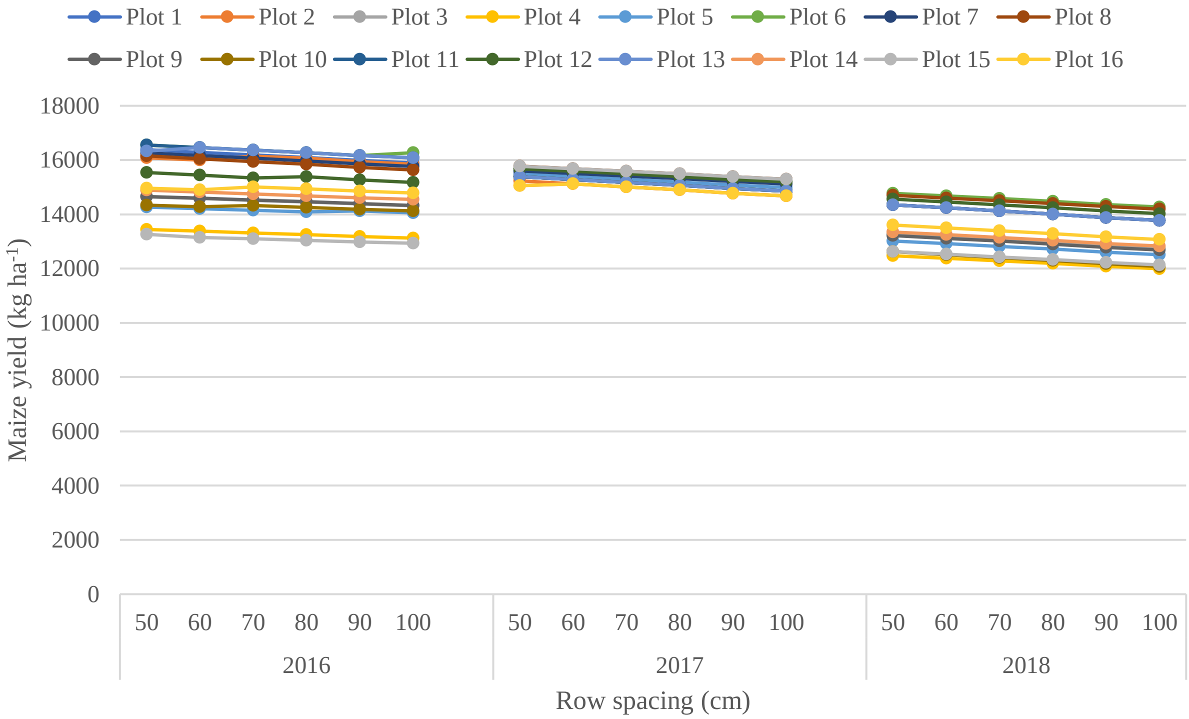


Figure 4.9 Modeled yield predictions of row spacing scenarios from 50 to 100 cm for all the plots during the 2016, 2017 and 2018 growing seasons.

The maize was planted on 91 cm rows for the field study. According to the model, if the row spacing was set at 50 cm, the yield would have been increased by 1.6% for C_E and 1.9% for

C_G during the 2016 growing season, 2.5% for C_E and 2.8% for C_G during the 2017 growing season, and 3.3% for C_E and 3.2% for C_G during the 2018 growing season. The yield increase would have been higher for the C_G compared to the C_E treatment during the 2016 and 2017 growing seasons, because maize was planted in the same plant density for both treatments, but the C_G was treated with higher fertilizer rates. However, the opposite results were observed during the 2018 growing season. Even if C_G was treated with higher fertilizer rates, the plant density was higher by approximately 24% compared to the C_E treatment, which would create more intra-row competition. This indicates that the row spacing, and plant density are correlated from their effect on yield.

Table 4.11 Average simulated maize yields (kg ha^{-1}) for the actual row spacing scenario (91 cm), and relative yield (%) compared to the row spacing scenarios of 50, 60, 70, 80, 90 and 100 cm for each growing season and treatment.

Row spacing (cm)								
Trt	**Year**	**Actual row spacing**	**50**	**60**	**70**	**80**	**90**	**100**
		Yield (kg ha^{-1})	**Relative yield (%)**					
C_E	2016	14088	101.6	101.1	100.9	100.4	100	99.6
	2017	15022	102.5	102.1	101.5	100.8	100	99.4
	2018	12603	103.3	102.5	101.7	100.9	100	99.2
C_G	2016	15910	101.9	101.5	100.9	100.4	100	99.3
	2017	15060	102.8	102.1	101.4	100.8	100	99.4
	2018	14023	103.2	102.4	101.7	100.9	100	99.3

Yield response to plant density

For the field study, maize was planted at the same seeding rates the first two growing seasons for both fertilizer treatments, which was approximately 79K plants ha^{-1}. The seeding rate was increased to approximately 98K plants ha^{-1} only for the C_G treatment in the 2018 growing season. However, the actual plant densities that were used as input into the model were based on the stand count at the end of the growing season, before harvesting. As a result, the actual plant densities varied between plots. DSSAT CERES-Maize model was used to run scenarios of plant densities between 70K and 130K plants ha^{-1} with a 10K plants ha^{-1} increment.

The yield response is consistent and has a linear relationship with plant density up to 120K plants ha^{-1}, regardless the growing season, treatment, and plot, while a yield decrease is predicted above 120K plants ha^{-1}. By increasing the plant density from 70K to 120K plants ha^{-1}, the yield increased by an average of 10.9% in 2016, 4.6% in 2017, and 9.4% in 2018. Yield was reduced, by an average of 4.3%, 7.1%, and 6.6% in 2016, 2017 and 2018, respectively, when the plant density increased from 120K to 130K plants ha^{-1}. This happened because of a barrenness in the model that is related to the ear weight per plant, which is reduced as plant size and ear size are reduced due to the higher density, triggering a threshold.

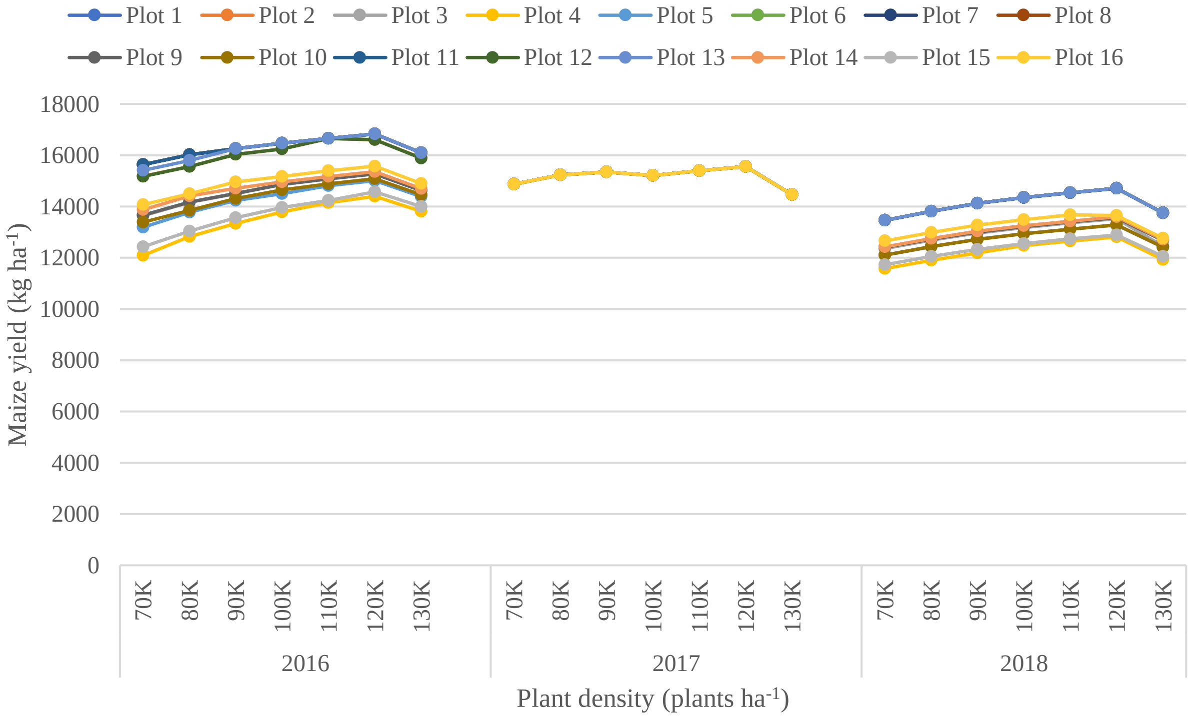


Figure 4.10 Modeled yield predictions of plant density scenarios from 70K to 130K plants ha^{-1} for all the plots during the 2016, 2017 and 2018 growing seasons.

According to the model, if 120K plants ha^{-1} were used for the field study, the yield could have been increased by 7.0% for C_E and 5.4% for C_G in 2016, 3.6% for C_E and 3.3% for C_G in 2017, and 5.7% for C_E and 4.9% for C_G in 2018.

Table 4.12 Average simulated maize yields (kg ha^{-1}) for the actual plant density scenario, and relative yield (%) compared to the plant density scenarios of 70K, 80K, 90K, 100K, 110K, 120K and 130K plants ha^{-1} for each growing season and treatment.

Plant density (plants ha^{-1})									
Trt	**Year**	**Actual plant density**	**70K**	**80K**	**90K**	**100K**	**110K**	**120K**	**130K**
		Yield (kg ha^{-1})	**Relative yield (%)**						
C_E	2016	14088	94.3	98.2	101.3	103.6	105.4	107	102.5
	2017	15022	99	101.4	102.2	101.3	102.5	103.6	96.3
	2018	12603	96.6	99.2	101.4	103.2	104.6	105.7	98.6
C_G	2016	15910	97.4	99.8	101.8	103.1	104.7	105.4	100.8
	2017	15060	98.7	101.1	101.9	101	102.2	103.3	96
	2018	14023	96	98.5	100.7	102.3	103.6	104.9	98

Yield response to N fertilizer rate

During the field study, high N fertilizer rates were applied to both treatments based on the professional recommendations of the UGA Extension (C_E) and Georgia maize Growers (C_G) for achieving maize yields of 22 and 28 Mg ha^{-1}, respectively. The N rates applied for the C_E treatment were 357, 383 and 302 kg N ha^{-1} during the 2016, 2017 and 2018 growing season, respectively, and for the C_G treatment 484, 593 and 504 kg N ha^{-1} during the 2016, 2017 and 2018 growing season, respectively. Scenarios of 150 to 650 kg N ha^{-1}, with 100 kg N ha^{-1} increment, were tested in the model for evaluating the maize yield and the Godwin method was used for the soil organic carbon.

According to the model, the higher the N rate the higher the yield, regardless of the growing season and plot. However, it was noticed that by increasing the N rate, the N use efficiency (NUE) was reduced in all cases. For instance, by increasing the N rate from 150 kg N ha^{-1} to 250 kg N ha^{-1}, the yield was increased by an average of 44.3%, 29.1%, and 14.1% in 2016, 2017 and 2018, respectively. However, when the N rate was increased from 250 kg N ha^{-1} to 350 kg N ha^{-1}, the yield was increased by an average of 13.8%, 12.2%, and 4.8% in 2016, 2017 and 2018, respectively. Consequently, the increment of yield increase is less as the N rate was increased. Higher yield responses were noticed in the 2016 growing season as the N rate was increased compared to the other two seasons. Before planting maize in 2016, the field was fallow and the initial conditions of NH_4-N and NO_3-N in the soil were lower compared to the other two years, which may explain the higher response. It should be mentioned that the model could not predict the yield goals of 22 Mg ha^{-1} and 28 Mg ha^{-1} for C_E and C_G treatment, respectively, with the selected scenarios of 150 kg N ha^{-1} to 650 kg N ha^{-1}. There is a possibility to continue to produce yield increases by applying more N fertilizers, but it would not be either efficient or profitable. This shows the significance of defining the amount of fertilizer that is necessary for achieving high maize yields because it can optimize growers’ financial productivity.

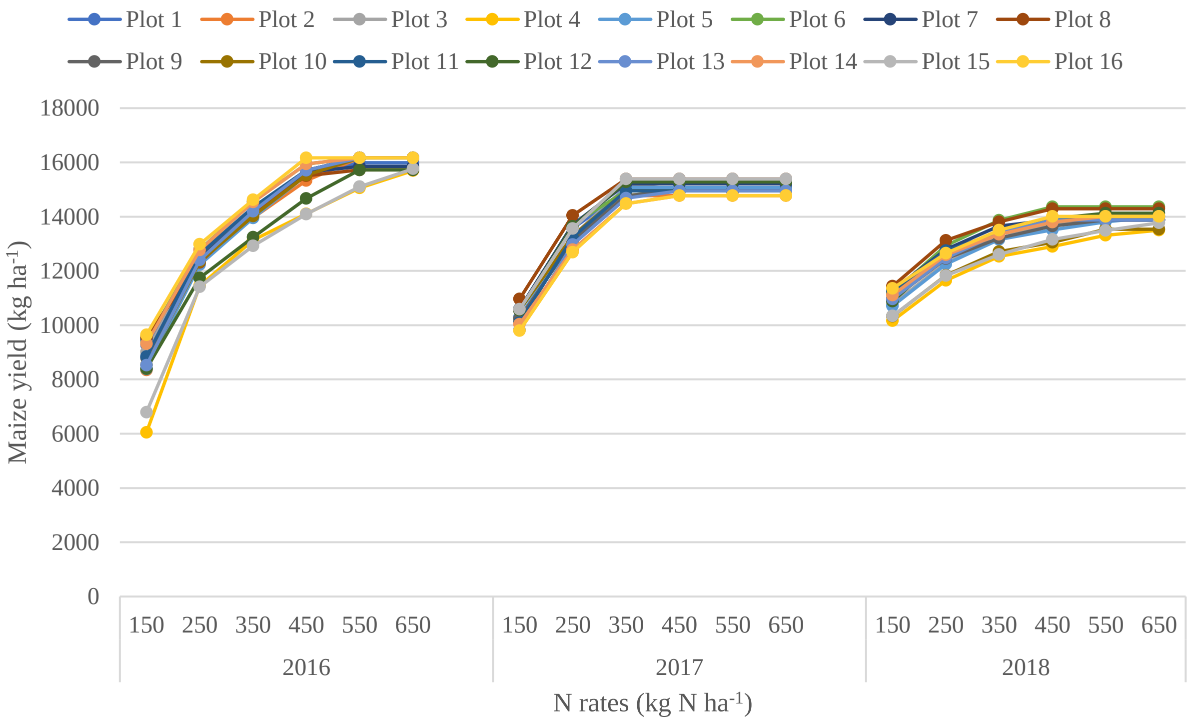


Figure 4.11 Modeled yield predictions of N fertilizer rates scenarios from 150 to 650 kg N ha^{-1} for all the plots during the 2016, 2017 and 2018 growing seasons.

According to the model's predictions, yield results similar to the actual N rates could have been achieved with lower N rates. For example, regarding the C_E treatment, the yield would have been lower by an average of 0.8% in 2016 and 0.9% in 2017, if 350 kg N ha^{-1} were applied. If 250 kg N ha^{-1} were applied the yield would have been lower than the actual scenario by 12.7%, 12.6% and 3.2% in 2016, 2017 and 2018, respectively. As for the C_G treatment, if 450 kg N ha^{-1} were applied the yield would have been reduced by an average of 2.6% in 2016, 0% in 2017 and 0.4% in 2018. If 350 kg N ha^{-1} were applied, it would result in yield reductions of 11.3%, 0.2% and 3.4% in 2016, 2017 and 2018, respectively. Consequently, NUE would have been increased if the C_E treatment had received 350 kg N ha^{-1} in 2016 and 2017, and 250 kg N ha^{-1} in 2018, and if the C$_G$ treatment had received 450 kg N ha^{-1} in 2016 and 350 kg N ha^{-1} the following two years. Increasing the N rates from the actual amount to 650 kg N ha^{-1}, caused both positive and no maize yield responses. More specifically, the yield would have been increased by an average of 14% in 2016 and 9.8% in 2018 for C$_E$ and 0.5% in 2016 for the C$_G$ treatment, while all the other cases showed no difference.

Table 4.13 Average simulated maize yields (kg ha^{-1}) for the actual N fertilizer rate scenario (C$_E$: 357, 383 and 302 kg N ha^{-1} for 2016, 2017 and 2018, respectively; C$_G$: 484, 593 and 504 kg N ha^{-1} for 2016, 2017 and 2018, respectively), and relative yield (%) compared to the N rate scenarios of 150, 250, 350, 450, 550 and 650 kg N ha^{-1} for each growing season and treatment.

N rate (kg N ha^{-1})								
Trt	**Year**	**Actual N**	**150**	**250**	**350**	**450**	**550**	**650**
		Yield (kg ha^{-1})	**Relative yield (%)**					
C$_E$	2016	14088	59	87.3	99.2	108.9	112.8	114
	2017	15022	68.2	87.4	99.1	100	100	100
	2018	12603	85	96.8	103.4	107	109.2	109.8
C$_G$	2016	15910	56.4	77.9	88.7	97.4	100.5	100.5
	2017	15060	69.1	89.8	99.8	100	100	100
	2018	14023	79.5	90.9	96.6	99.6	100	100

Yield response to number of N side-dress applications

After the pre-plant and at planting N fertilizer applications, the remaining amount of N was split into several side-dress applications. However, the number of side-dress applications was not consistent between the three growing seasons and two treatments during the field study. More specifically, there were 2 side-dress applications for both treatments in 2016, 2 for C$_E$ and 6 for C$_G$ in 2017, and 3 for C$_E$ and 4 for C$_G$ in 2018. DSSAT CERES-Maize was used to test how splitting the N side-dress into a lower or higher number of applications could influence the yield results. Six scenarios of 1 to 6 splits, were evaluated.

Apart from the 2017 growing season in which the yield results were not affected by the number of N side-dress applications, a positive response to a higher number of side-dress applications was noticed in the other two years. Applying all the N in 1 side-dress application had the lowest maize yield. However, the yield was increased by an average of 5% in 2016 and 7.4% in 2018 for C_E and 0.5% in 2016 for C_G when the N was split into 6 side-dress applications. Splitting the N rate into more side-dress applications prevents N from being lost through runoff or leaching. This management prevents N stresses, since by applying N later in the season, when it is needed most, plants have better access to it. The yield of C_E treatment had greater response to higher rates than the C_G treatment that did not show many differences between the scenarios. A likely explanation is that more fertilizer was provided by the C_G treatment making the approach of splitting irrelevant. The predicted yield results of 2017 might be the consequence of the highest amounts of fertilizer that was applied during that year compared to the other two. Additionally, since 2017 was the driest year of all three, less N leaching occurred, according to the simulated results of Pavlou et al. (2020b). It is important to make decisions about how to split the N fertilizer not only for increasing maize yield but because it is a time-consuming process, which is getting difficult as the plants are getting taller.

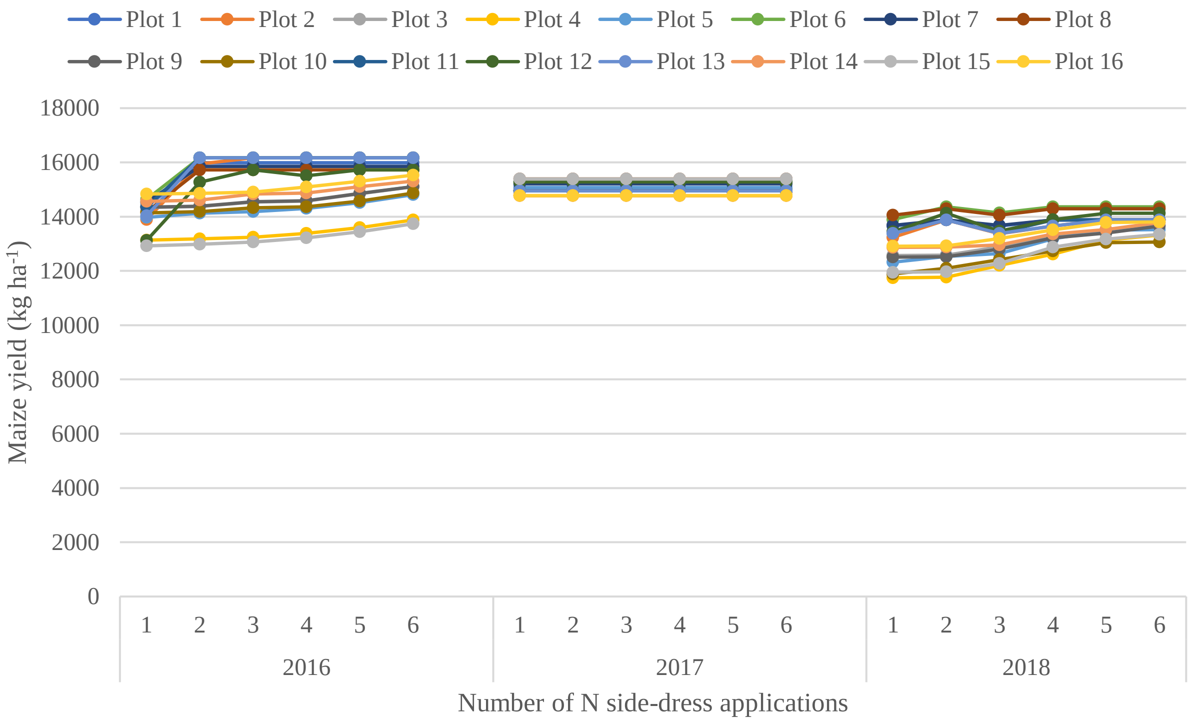


Figure 4.12 Modeled yield predictions of number of N side-dress applications scenarios from 1 to 6 splits for all the plots during the 2016, 2017 and 2018 growing seasons.

Table 4.14 Average simulated maize yields (kg ha^{-1}) for the actual number of N side-dress applications scenario (C_E: 2, 2 and 3 for 2016, 2017 and 2018, respectively; C_G: 2, 6 and 4 for 2016, 2017 and 2018, respectively), and relative yield (%) compared to the number of N side-dress application scenarios of 1, 2, 3, 4, 5 and 6 for each growing season and treatment.

		Number of N side-dress applications						
Trt	**Year**	**Actual**	**1**	**2**	**3**	**4**	**5**	**6**
		Yield (kg ha^{-1})	**Relative yield (%)**					
C_E	2016	14088	99.6	100	100.8	101.5	103.1	105
	2017	15022	100	100	100	100	100	100
	2018	12603	97.9	98.5	100	103.9	106.2	107.4
C_G	2016	15910	88.9	100	100.5	100.4	100.5	100.5
	2017	15060	100	100	100	100	100	100
	2018	14023	96.9	97.3	99.4	100	100	100

Yield response to timing of side-dress N applications

During the field study, the first N side-dress was applied 2 WAP in 2016 and 2017 and 3 WAP in 2018. In DSSAT CERES-Maize model, four scenarios of applying the N side-dress 2 to 5 WAP, with one-week intervals, were evaluated in terms of maize yield. The following side-dress applications were adjusted accordingly based on the actual scenario.

The yield response to timing of side-dress N applications were similar to the scenarios of the number of N side-dress applications. In most cases, applying the first N side-dress 2 WAP would result in lower yields, while if the first N side-dress application was applied 5 WAP, it would have a positive impact on yield results up to 7.8% (2018, Plot 4) for C_E and 5.4% (2016, Plot 12) for C_G compared to the 2 WAP. The timing of N side-dress applications had a greater impact on yield results of C_E than C_G treatment, while no response was noticed in both treatments during 2017 growing season, probably for the same reasons described earlier.

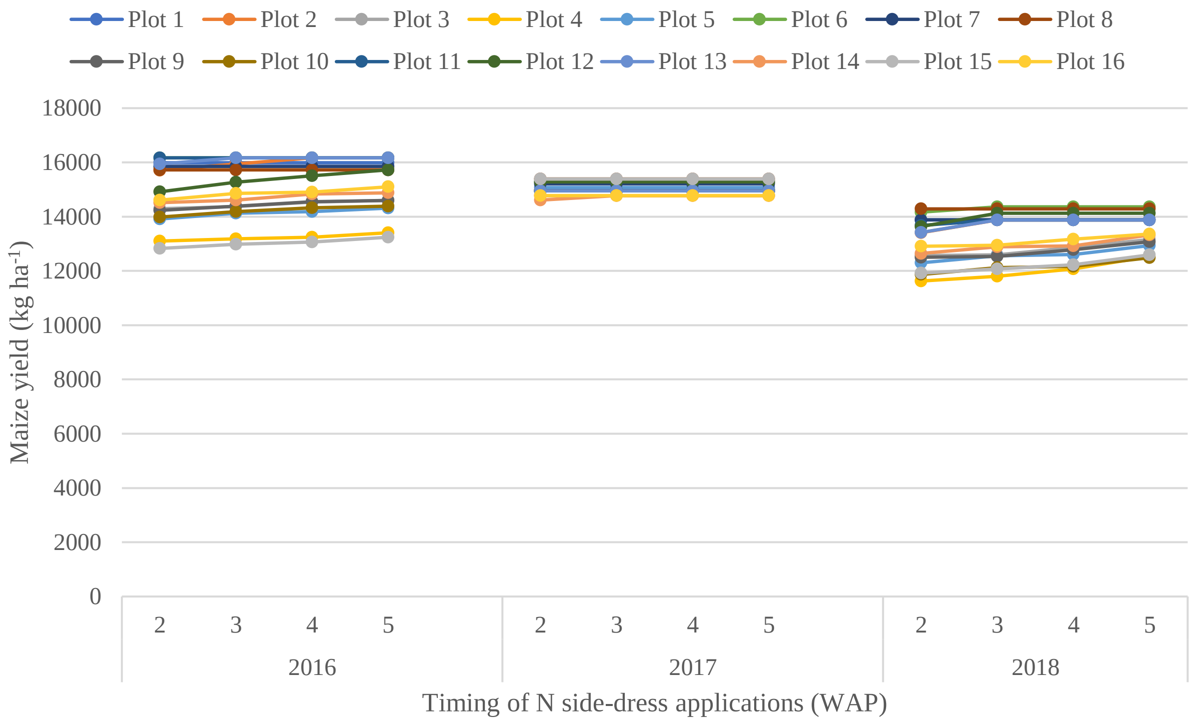


Figure 4.13 Modeled yield predictions of timing of N side-dress applications scenarios from 2 to 5 WAP for all the plots during the 2016, 2017 and 2018 growing seasons.

Decisions about the timing of N side-dress applications are important to ensure that the plants have adequate N when they need it for avoiding nutrient stresses. Also, applying fertilizers later in the season might be challenging due to the size of the crop. During the 2016 growing season, the yield could have been increased by 1.6% for C_E and 0.5% for C_G if the first N side-dress was applied 5 WAP compared to the actual scenarios. However, there were plots that provided the same yields when the first side-dress was applied earlier. During the 2018 growing season, applying the first N side-dress 5 WAP compared to the actual, would provide by an average increase of 2.6% in yield for the C_E treatment. As for the C_G treatment, the same yield results to the actual scenario (4 WAP) would have been achieved if the first N side-dress was applied 3 WAP.

Table 4.15 Average simulated maize yields (kg ha^{-1}) for the actual timing of N side-dress applications scenario (3, 3 and 4 WAP for 2016, 2017 and 2018), and relative yield (%) compared to the timing of N side-dress application scenarios of 2, 3, 4, and 5 WAP for each growing season and treatment.

Timing of N side-dress applications (WAP)						
Trt	**Year**	**Actual**	**2**	**3**	**4**	**5**
		Yield (kg ha^{-1})	**Relative yield (%)**			
C_E	2016	14088	98.9	100	100.8	101.6
	2017	15022	99.9	100	100	100
	2018	12603	97.5	98.7	100	102.6
C_G	2016	15910	99.4	100	100.4	100.5
	2017	15060	100	100	100	100
	2018	14023	98.4	100	100	100

Yield response to irrigation scenarios

The yield response to three irrigation scenarios was evaluated in DSSAT CERES-Maize. The actual scenario referred to the sensor-based method, in which the irrigation was based on soil moisture sensor readings. The other two scenarios referred to the UGA Extension Checkbook method, in which the irrigation was based on historical ET data, and the rainfed treatment, in which no irrigation was applied.

The model predicted higher yield with the sensor-based irrigation scheduling method followed by the checkbook method regardless of year, treatment, and plot. More specifically, the UGA Extension Checkbook produced less yield than the sensor-based by 5.6% for C_E and 7.3% for C_G in 2016, 20.5% for C_E and 11.6% for C_G in 2017, and 7.3% for C_E and 2.3% for C_G in 2018. The model predicted higher N stresses from the end of grain filling to the harvest period for the UGA Extension Checkbook compared to the sensor-based method. The extra water application could have leached out the N. The rainfed treatment resulted in even lower yields by 89.7%, 53.5% and 12.2% for C_E and 90.5%, 54.5% and 19.5% for C_G in 2016, 2017 and 2018, respectively, due to water stress from silking to the end of the growing seasons. By using the UGA Extension Checkbook method 21%, 140%, and 50% more water would have applied (Table 4.6) in comparison to the sensor-based method in 2016, 2017 and 2018 growing season, respectively. This shows that more water does not necessarily lead to higher yields because it can leach out the N. Generally, the water use efficiency (WUE), which is the ratio between yield and water received, decreased as the amount of irrigation increases. Furthermore, higher amounts of water could result in excessive nutrient leaching below the root zone as it was shown in the simulation study for these scenarios by Pavlou et al. (2020c), which could have negative effects on the maize yield. Besides the amount of water applied, the right timing of irrigation is very important too. The sensor-based method triggers irrigation when the SWT reaches the threshold of 30 kPa - 35 kPa, preventing water stress. As expected, the rainfed treatment had the lowest yields not only because less water was received compared to the other two treatments but due to the timing of the rainfall events. The model indicated higher water stress during 2016 than 2018 growing season for the rainfed treatment because the plots received 87.4 mm less rain during the grain filling period, which slowed the grain filling process. As a result, lower yields were predicted during the 2016 growing season for the rainfed treatment.

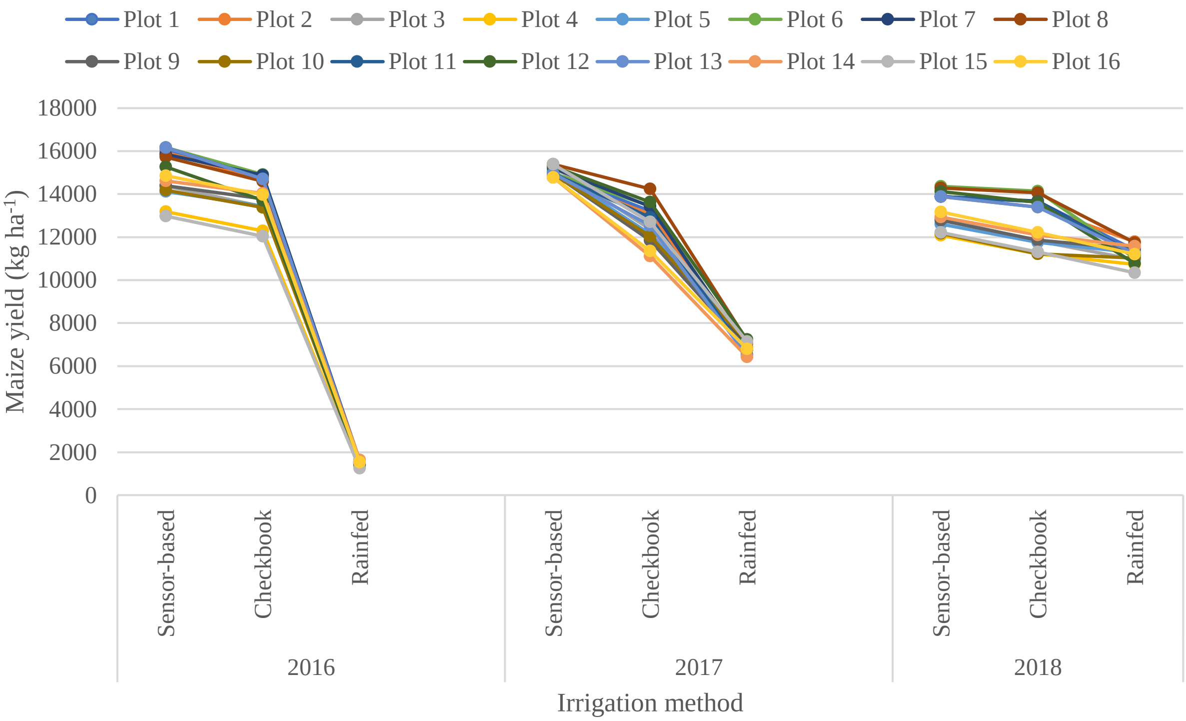


Figure 4.14 Modeled yield predictions of sensor-based, UGA Extension Checkbook, and rainfed irrigation scenarios for all the plots during the 2016, 2017 and 2018 growing seasons.

Table 4.16 Average simulated maize yields (kg ha^{-1}) for the actual irrigation scenario (sensor-based method), and relative yield (%) compared to the irrigation scenarios of the UGA Extension Checkbook method and rainfed treatment for each growing season and treatment.

		Irrigation treatment		
Trt	**Year**	**Actual: Sensor-based**	**UGA Extension Checkbook**	**Rainfed**
		Yield (kg ha^{-1})	**Yield increase or decrease (%)**	
C_E	2016	14088	94.4	10.3
	2017	15022	79.5	46.5
	2018	12603	92.7	87.8
C_G	2016	15910	91.9	9.5
	2017	15060	88.4	45.5
	2018	14023	97.7	80.5

Discussion and conclusions

In the quest for increasing maize yields, farmers should put their attention and effort into finding the best management practices that can assist them in achieving that goal. Field variability, government policies, new varieties, farm equipment etc. can make the decision-making process a difficult task. However, the correct evaluation of the available data can lead to increased maize yields which can have a positive economic impact for growers. Such an evaluation can be done with the use of simulation models, such as DSSAT CERES-Maize. This model was used to conduct an analysis in which several management scenarios regarding planting, fertilization and irrigation were simulated in terms of yield and compared to the actual practices followed in a three-year field study in Tifton, GA, by Orfanou et al. (2020a).

Planting date is an important factor in maize production since the weather conditions can influence emergence, growth, and development, which can have a significant impact on the final yield. In Georgia, maize is normally planted during early spring. In this study, the model showed that there was a specific window for planting during the three years of the field study that could result in achieving higher yields. The optimum planting period varied from year to year. However, the planting period can vary due to the bounce planting date effects of the model, mostly because the grain number is set by the solar radiation during an approximate nine-day period before grain growth begins. A study conducted in Oklahoma showed that maize yield was decreased by 225 kg ha^{-1} day^{-1} to 1379 kg ha^{-1} day^{-1} for each day the emergence was delayed (Lawles et al., 2012). A similar comparison was made in Southwestern Ontario and the results of DSSAT CERES-Maize showed that maize planted 5 to 10 days earlier than May 24, produced 13% to 19% less yield. By planting up to 10 days later than May 24 would have produced similar yield results (He et al., 2016).

Maize seeds should absorb 30% of their weight in water to germinate, for that reason they should be planted at a depth where there is adequate moisture. By planting maize seeds at a proper depth, a strong nodal root system can be created, which can prevent lodging and help maize plants when they are under drought conditions. In general, maize should not be planted at less than a 3.5 cm depth, while if it is planted up to 8 cm deep high yield results can be obtained, as it was shown by the model. A study that took place in Ohio from 2017 to 2019, stated that planting maize seeds from 4 to 8 cm depth can be beneficial as the soil becomes warmer and drier as the season progresses. Furthermore, their results showed a 9% to 10% yield reduction when maize was planted at 2.5 cm depth compared to 5 cm and 7.5 cm. However, in the same study, in a low organic matter trial, the maize yield results were similar (Lindsey et al., 2020).

The model in this study predicted higher maize yields in narrower row spacing. Narrow row spacing reduces intra-row competition for water, nutrients and light and increases faster canopy closure, which provides more shading. Shading improves weed control and reduces water loss through evaporation. A study conducted in Nebraska, in which 51cm and 76 cm row spacing were compared, showed that row spacing of 51 cm had higher yield results in two out of three years of the project. In the third year, however, 76 cm row spacing produced higher maize yields (Shapiro and Wortmann, 2006). This is an indication that meteorological conditions along with management practices followed can influence the final yield. Proper decisions about row spacing should also consider the plant density as well. In this study, simulated plant densities of 120K plants ha^{-1} had the highest maize yields. Yields decreased when the plant density was increased to 130K plants ha^{-1} due to competition between plants. This comes into agreement with the results of a study conducted in Georgia by Orfanou et al. (2019), which showed that in most cases the yield was increased for plant densities up to 99K plants ha^{-1}, while the yield was decreased at 133K plants ha^{-1}. Consequently, higher maize densities do not necessarily mean higher yields. A study conducted in Iowa showed that there were either no yield differences or reduction of maize yield by increasing the plant density from 75K to 104K plants ha^{-1} (Licht et al., 2019). Similarly to narrow row spacing, twin-rows can be used for increasing yields as it was shown by Jones (2010). In their study, twin-rows of 19 cm wide on 76 cm centers had 12.5% higher yield than traditional 76 cm rows.

N fertilizer is an important factor for achieving high maize yield. Typically, growers apply high rates of fertilizer to achieve high maize yields. Farmers use a yield goal approach to decide the N fertilizer rate, i.e. 1.12 kg N to 1.35 kg N for 25.4 kg of maize yield expected. This approach might be successful to some extent. As it was presented in this study, DSSAT CERES-Maize predicted higher maize yields when the N fertilizer rates were increased up to a certain point. Applying even higher rates of N was not an efficient approach since the yield results did not show considerable difference. These results agree with other studies. In a study which used CERES-Maize model to test N rates from 0 to 300 kg ha^{-1}, the maximum yield was achieved at 212 kg ha^{-1}, while there were no statistical differences between the 150 to 300 kg ha^{-1} range (He et al., 2016). Similar results were produced by CERES-Maize model in a study that showed that maximum yield would have been produced at 240 kg ha^{-1} instead of 300 kg ha^{-1} which was the highest fertilizer rate tested (Jiang et al., 2019). Before determining the amount of fertilizer, factors such as soil and weather conditions, field variability, topography should be taken into account because higher N fertilizer rates might cause N leaching as it has been shown by Pavlou et al. (2020a).

By applying fertilizers at the right time, nutrients become available to the plants when they are needed. Fertilizer applications at the right time and smaller doses, can meet the demands of maize plants by assisting their growth and development. By splitting the fertilizer into more than one side-dress application, yield results can be improved as was shown in several cases by the results of the model. This happens because there are fewer chances of nutrients being lost through surface runoff or leaching. Previous studies have shown that splitting the fertilizer, based on crop demands, can increase the NUE which can have a positive impact in the final yield (Niu et al., 2013; Yang et al., 2011a). Furthermore, a study in Kansas showed that a N application of 20% at planting, 40% at V6 and 40% at V10 stages can produce higher maize yield results (Gehl et al., 2005).

Farmers feel comfortable using more traditional methods such as checkbook methods for irrigation scheduling since they are familiar with them. Nevertheless, the use of soil moisture sensors for irrigation scheduling can have many advantages. It does not only assist in increasing maize yields, but in reducing NO_3-N leaching compared to the UGA Checkbook method, as shown in a simulation study by Pavlou et al. (2020c). Furthermore, studies in Georgia and Alabama have shown that the use of a sensor-based method requires less irrigation water to produce similar maize yield results compared to a checkbook method (Filho, 2016; Orfanou et al., 2019).

In conclusion, the results of this study showed that the DSSAT-CERES maize model was used effectively at evaluating relative differences of management practices. This is an indication that the optimization of management practices for maize can be accomplished using advanced tools such as simulation models. Making decisions about maize production are complex and important choices are required to be made throughout the season for maximizing yields. As it was shown, meteorological conditions, are crucial in the decision-making process, as they might influence the outcome of management practices such as planting date or irrigation. The analysis of different scenarios, via models, can enhance management, nutrient and water use efficiency and yields which can improve farmers’ financial prosperity and reduce their environmental footprint.

CHAPTER 5

CONCLUSIONS

The yield goals of the C_E and C_G treatments, which were 22 Mg ha^{-1} and 28 Mg ha^{-1}, respectively, were not achieved during any of the growing seasons of this study, which was conducted in Tifton, GA. Reasons for not achieving the yield goals were the sandy soil of the field, which was low in CEC and pH, and the meteorological conditions. The higher solar radiation and lower minimum temperature during the 2016 growing season, resulted in significant higher yields compared to the 2017 and 2018 growing seasons. The N rates for both C_E and C_G treatments were high enough, which resulted in no significant differences in terms of yield between the two treatments.

Meteorological, soil and plant data as well as information about the management practices followed during the three growing seasons of the field study were used for setting up the DSSAT CERES-Maize model. The DSSAT CERES-Maize model was used successfully for calibrating the cultivar coefficients, which were adjusted to achieve a good fit between simulated and observed values of leaf number per stem, leaf weight, vegetative N concentration and grain yield. The successful calibration was confirmed with the evaluation results. In both calibration and evaluation processes, the r^2 and d-stat had values close to 1.

The calibrated model was used to identify the limitations in agronomic management practices for pursuing high maize yields. Scenarios regarding the planting date, planting depth, row spacing, plant density, N fertilizer rates, number of N side-dress applications, timing of side-dress N applications and irrigation scenarios were evaluated. The results of this study showed that the DSSAT-CERES maize model was used effectively for evaluating relative differences of management practices. This is an indication that the optimization of management practices for maize can be accomplished using advanced tools such as simulation models. Making decisions about maize production are complex and important choices are required to be made throughout the season for maximizing yields. As it was shown, meteorological conditions, are crucial in the decision-making process, as they might influence the outcome of management practices such as planting date or irrigation. The analysis of different scenarios, via models, can enhance management, nutrient and water use efficiency and yields which can improve farmers’ financial prosperity and reduce their environmental footprint.

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APPENDIX A

SOIL ANALYSIS

Mean values of OM, CEC, pH, macronutrients and micronutrients at various depths for each treatment and sampling event. Means followed by different letters between fertilization treatments within the same sampling event and depth, between fertilization treatments withing the same sampling depth, between sampling events within the same fertilization treatment and depth, and between depths are significantly different ($p - value < 0.05$).

Depth (m)	Date	Trt	OM (%)	CEC (cmol(+) kg^{-1})	pH	P	K	Ca	Mg	S	Mn	Zn	Fe	Cu	B
						(kg ha^{-1})									
0-0.15	By fertilization treatment														
	Feb 2016	C_E	N/A	3.7^{a}	5.9^{a}	89.6^{a}	154.5^{a}	624.2^{a}	69.4^{a}	45.1^{a}	17.8^{a}	3.4^{a}	75.8^{a}	0.5^{a}	0.3^{a}
		C_G	N/A	3.8^{a}	6.0^{a}	89.4^{a}	149.1^{a}	712.4^{a}	82.6^{a}	44.9^{a}	19.2^{a}	4.7^{a}	80.7^{a}	0.6^{a}	0.3^{a}
	Sep 2016	C_E	0.7^{a}	4.0^{a}	5.8^{a}	81.9^{a}	93.2^{b}	696.6^{a}	81.5^{a}	48.0^{a}	14.2^{a}	4.4^{b}	65.7^{a}	0.6^{a}	0.5^{a}
		C_G	0.8^{a}	4.4^{a}	5.8^{a}	90.2^{a}	132.9^{a}	754.1^{a}	90.9^{a}	29.6^{a}	17.6^{a}	7.4^{a}	72.3^{a}	0.7^{a}	0.5^{a}
	Feb 2017	C_E	0.5^{a}	5.4^{a}	6.0^{a}	187.3^{a}	101.9^{a}	1410.7^{a}	163.9^{a}	46.1^{a}	37.5^{a}	8.4^{a}	155.6^{a}	0.8^{a}	0.4^{a}
		C_G	0.5^{a}	5.0^{a}	6.2^{a}	173.1^{a}	108.7^{a}	1435.8^{a}	169.3^{a}	48.0^{a}	30.3^{a}	10.1^{a}	119.7^{a}	0.7^{a}	0.5^{a}
	Sep 2017	C_E	0.5^{a}	5.2^{a}	6.8^{a}	166.9^{a}	131.8^{a}	1722.5^{a}	178.2^{a}	39.2^{a}	17.1^{a}	9.5^{a}	92.8^{a}	0.8^{a}	1.1^{a}
		C_G	0.5^{a}	4.9^{a}	6.8^{a}	172.4^{a}	164.4^{a}	1574.0^{a}	179.3^{a}	40.0^{a}	17.4^{a}	12.8^{a}	96.6^{a}	0.8^{a}	1.0^{a}
	Feb 2018	C_E	1.0^{a}	3.7^{a}	6.9^{a}	108.9^{a}	103.2^{a}	1210.1^{a}	137.4^{a}	73.6^{a}	14.5^{a}	6.8^{a}	51.6^{a}	0.4^{a}	0.6^{a}
		C_G	1.0^{a}	4.0^{a}	6.9^{a}	112.6^{a}	115.2^{a}	1279.0^{a}	134.3^{a}	91.3^{a}	15.4^{a}	9.0^{a}	51.8^{a}	0.6^{a}	0.6^{a}
	Sep 2018	C_E	1.0^{a}	7.8^{a}	6.9^{a}	253.7^{a}	270.4^{a}	2552.7^{a}	347.2^{a}	61.4^{a}	28.7^{a}	20.9^{b}	112.7^{a}	17.3^{a}	0.8^{a}
		C_G	1.1^{a}	7.4^{a}	6.7^{b}	280.1^{a}	309.9^{a}	2365.8^{a}	345.5^{a}	55.3^{b}	33.7^{a}	32.2^{a}	132.7^{a}	17.4^{a}	0.9^{a}
	Mean	C_E	0.7^{a}	5.0^{a}	6.4^{a}	148.0^{a}	141.9^{a}	1370.2^{a}	163.1^{a}	52.3^{a}	21.6^{a}	8.9^{b}	92.3^{a}	3.4^{a}	0.6^{a}
		C_G	0.8^{a}	4.9^{a}	6.4^{a}	153.6^{a}	163.5^{a}	1360.3^{a}	167.9^{a}	51.6^{a}	22.3^{a}	12.8^{a}	92.4^{a}	3.5^{a}	0.7^{a}
	By soil sampling event														

Depth (m)	Date	Trt	OM (%)	CEC (cmol(+) kg^{-1})	pH	P	K	Ca	Mg	S	Mn	Zn	Fe	Cu	B
						(kg ha^{-1})									
	Feb 2016	C_E		3.7^{c}	5.9^{bc}	89.6^{c}	154.5^{b}	624.2^{d}	69.4^{c}	45.1^{a}	17.8^{bc}	3.4^{c}	75.8^{cd}	0.5^{b}	0.3^{c}
	Sep 2016		0.7^{b}	4.0^{c}	5.8^{c}	81.9^{c}	93.2^{c}	696.6^{d}	81.5^{c}	48.0^{a}	14.2^{c}	4.4^{bc}	65.7^{cd}	0.6^{b}	0.5^{bc}
	Feb 2017		0.5^{c}	5.4^{b}	6.0^{b}	187.3^{b}	101.9^{c}	1410.7^{bc}	163.9^{b}	46.1^{a}	37.5^{a}	8.4^{bc}	155.6^{a}	0.8^{b}	0.4^{c}
	Sep 2017		0.5^{c}	5.2^{b}	6.8^{a}	166.9^{b}	131.8^{bc}	1722.5^{b}	178.2^{b}	39.2^{a}	17.1^{bc}	9.5^{b}	92.8^{bc}	0.8^{b}	1.1^{a}
	Feb 2018		1.0^{a}	3.7^{c}	6.9^{a}	108.9^{c}	103.2^{c}	1210.1^{c}	137.4^{b}	73.6^{a}	14.5^{c}	6.8^{bc}	51.6^{d}	0.4^{b}	0.6^{bc}
	Sep 2018		1.0^{a}	7.8^{a}	6.9^{a}	253.7^{a}	270.4^{a}	2552.7^{a}	347.2^{a}	61.4^{a}	28.7^{ab}	20.9^{a}	112.7^{b}	17.3^{a}	0.8^{ab}
	Feb 2016	C_G		3.8^{c}	6.0^{c}	89.4^{c}	149.1^{b}	712.4^{c}	82.6^{e}	44.9^{bc}	19.2^{b}	4.7^{b}	80.7^{cd}	0.6^{b}	0.3^{c}
	Sep 2016		0.8^{bc}	4.4^{bc}	5.8^{c}	90.2^{c}	132.9^{b}	754.1^{c}	90.9^{de}	29.6^{c}	17.6^{b}	7.4^{b}	72.3^{cd}	0.7^{b}	0.5^{bc}
	Feb 2017		0.5^{c}	5.0^{b}	6.3^{b}	173.1^{b}	108.7^{b}	1435.8^{b}	169.3^{bc}	48.0^{bc}	30.3^{a}	10.1^{b}	119.7^{ab}	0.7^{b}	0.5^{bc}
	Sep 2017		0.5^{c}	4.9^{b}	6.8^{a}	172.4^{b}	164.4^{b}	1574.0^{b}	179.3^{b}	40.0^{bc}	17.4^{b}	12.8^{b}	96.6^{bc}	0.8^{b}	1.0^{a}
	Feb 2018		1.0^{ab}	3.9^{c}	6.9^{a}	112.6^{c}	115.2^{b}	1279.0^{b}	134.3^{cd}	91.3^{a}	15.4^{b}	9.0^{b}	51.8^{d}	0.6^{b}	0.6^{abc}
	Sep 2018		1.1^{a}	7.4^{a}	6.7^{a}	280.1^{a}	309.9^{a}	2365.8^{a}	345.5^{a}	55.3^{b}	33.7^{a}	32.2^{a}	132.7^{a}	17.4^{a}	0.9^{ab}
0.15-0.3	By fertilization treatment														
	Feb 2016	C_E		3.9^{a}	6.0^{a}	90.9^{a}	137.7^{a}	794.8^{a}	90.2^{a}	46.0^{a}	16.9^{a}	3.5^{a}	98.3^{a}	0.7^{a}	0.4^{a}
		C_G		3.8^{a}	6.1^{a}	87.7^{a}	132.7^{a}	822.1^{a}	95.1^{a}	43.9^{a}	18.0^{a}	3.6^{a}	89.2^{a}	0.7^{a}	0.3^{a}
	Sep 2016	C_E	0.7^{a}	4.0^{a}	5.7^{a}	77.4^{a}	63.9^{b}	646.3^{a}	64.0^{a}	34.9^{a}	13.9^{a}	3.2^{a}	81.2^{a}	0.8^{a}	0.5^{a}
		C_G	0.8^{a}	4.1^{a}	5.7^{a}	66.5^{a}	86.6^{a}	673.8^{a}	65.9^{a}	37.0^{a}	12.4^{a}	4.7^{a}	69.2^{a}	0.7^{a}	0.6^{a}
	Feb 2017	C_E	0.4^{b}	5.0^{a}	5.6^{b}	169.2^{a}	99.6^{b}	863.5^{a}	85.7^{a}	43.1^{a}	33.6^{a}	5.0^{a}	180.6^{a}	0.6^{a}	0.3^{a}
		C_G	0.5^{a}	4.6^{a}	5.8^{a}	131.0^{a}	121.6^{a}	931.6^{a}	98.3^{a}	48.8^{a}	26.8^{a}	5.4^{a}	133.4^{a}	0.7^{a}	0.4^{a}
	Sep 2017	C_E	0.4^{a}	3.9^{a}	6.0^{b}	93.0^{a}	119.0^{b}	813.2^{b}	88.1^{b}	36.4^{a}	11.6^{a}	3.9^{a}	87.4^{a}	0.7^{a}	0.8^{a}
		C_G	0.4^{a}	4.1^{a}	6.2^{a}	93.2^{a}	151.6^{a}	960.2^{a}	112.9^{a}	42.5^{a}	12.5^{a}	6.5^{a}	89.0^{a}	0.8^{a}	1.0^{a}
	Feb 2018	C_E	0.9^{a}	3.6^{a}	6.1^{a}	71.5^{a}	76.3^{b}	713.2^{a}	83.4^{a}	58.8^{a}	9.8^{a}	6.7^{a}	98.2^{a}	1.4^{a}	0.7^{a}
		C_G	0.9^{a}	3.6^{a}	6.2^{a}	58.5^{a}	109.2^{a}	745.9^{a}	100.0^{a}	59.0^{a}	11.3^{a}	4.6^{a}	58.7^{a}	0.4^{a}	0.6^{a}
	Sep 2018	C_E	0.7^{a}	5.6^{b}	6.4^{a}	147.4^{a}	184.0^{a}	1626.4^{a}	207.4^{b}	63.1^{a}	17.7^{a}	13.0^{b}	116.1^{a}	12.2^{b}	0.8^{a}
		C_G	0.7^{a}	6.7^{a}	6.3^{a}	160.0^{a}	206.9^{a}	1848.8^{a}	289.3^{a}	57.4^{a}	22.8^{a}	19.6^{a}	133.3^{a}	18.6^{a}	1.0^{a}
	Mean	C_E	0.6^{a}	4.3^{a}	6.0^{b}	108.1^{a}	112.7^{b}	908.0^{a}	102.9^{b}	46.9^{a}	17.2^{a}	5.9^{a}	110.1^{a}	2.7^{a}	0.6^{a}
		C_G	0.7^{a}	4.5^{a}	6.1^{a}	99.6^{a}	134.8^{a}	998.9^{a}	127.3^{a}	48.1^{a}	17.3^{a}	7.4^{a}	95.7^{a}	3.7^{a}	0.7^{a}
	By soil sampling event														

Depth (m)	Date	Trt	OM (%)	CEC (cmol(+) kg^{-1})	pH	P	K	Ca	Mg	S	Mn	Zn	Fe	Cu	B
						(kg ha^{-1})									
	Feb 2016	C$_{E}$		3.9^{b}	6.0^{b}	90.9^{bc}	137.7^{b}	794.8^{b}	90.2^{b}	46.0^{bc}	16.9^{b}	3.5^{b}	98.3^{b}	0.7^{b}	0.4^{cd}
	Sep 2016		0.7^{b}	4.0^{b}	5.7^{c}	77.4^{c}	63.9^{c}	646.3^{b}	64.0^{b}	34.9^{c}	13.1^{b}	3.2^{b}	81.2^{b}	0.8^{b}	0.5^{bcd}
	Feb 2017		0.4^{c}	5.0^{a}	5.6^{c}	169.2^{a}	99.6^{bc}	863.5^{b}	85.7^{b}	43.1^{bc}	33.6^{a}	5.0^{b}	180.6^{a}	0.6^{b}	0.3^{d}
	Sep 2017		0.4^{c}	3.9^{b}	6.0^{b}	93.0^{bc}	119.0^{b}	813.2^{b}	88.1^{b}	36.4^{c}	11.6^{b}	3.9^{b}	87.4^{b}	0.7^{b}	0.8^{ab}
	Feb 2018		0.9^{a}	3.6^{b}	6.1^{ab}	71.5^{c}	76.3^{c}	713.2^{b}	83.4^{b}	58.8^{ab}	9.8^{b}	6.7^{b}	98.2^{b}	1.4^{b}	0.7^{abc}
	Sep 2018		0.7^{b}	5.6^{a}	6.4^{a}	147.5^{ab}	184.0^{a}	1626.4^{a}	207.4^{a}	63.1^{a}	17.7^{b}	13.0^{a}	116.1^{b}	12.2^{a}	0.8^{a}
	Feb 2016	C$_{G}$		3.8^{bc}	6.1^{ab}	87.7^{bc}	132.7^{bc}	822.1^{b}	95.1^{b}	43.9^{bc}	18.0^{bc}	3.6^{b}	89.2^{b}	0.7^{b}	0.3^{c}
	Sep 2016		0.8^{a}	4.1^{bc}	5.7^{c}	66.5^{c}	86.6^{c}	673.8^{b}	65.9^{b}	37.0^{c}	12.4^{c}	4.7^{b}	69.2^{b}	0.7^{b}	0.6^{bc}
	Feb 2017		0.5^{b}	4.6^{b}	5.8^{bc}	131.0^{ab}	121.6^{bc}	931.6^{b}	98.3^{b}	48.8^{abc}	26.8^{a}	5.4^{b}	133.4^{a}	0.7^{b}	0.4^{c}
	Sep 2017		0.4^{b}	4.1^{bc}	6.2^{a}	93.2^{bc}	151.6^{b}	960.2^{b}	112.9^{b}	42.5^{c}	12.5^{c}	6.5^{b}	89.8^{b}	0.8^{b}	1.0^{a}
	Feb 2018		0.9^{a}	3.6^{c}	6.2^{a}	58.5^{c}	109.2^{bc}	745.9^{b}	100.0^{b}	59.0^{a}	11.3^{c}	4.6^{b}	58.7^{b}	0.4^{b}	0.6^{bc}
	Sep 2018		0.7^{a}	6.7^{a}	6.3^{a}	160.0^{a}	206.9^{a}	1848.8^{a}	289.3^{a}	57.4^{ab}	22.8^{ab}	19.6^{a}	133.3^{a}	18.6^{a}	1.0^{ab}
0.3-0.45	By fertilization treatment														
	Feb 2016	C$_{E}$		4.0^{a}	5.8^{a}	18.2^{a}	101.2^{a}	640.7^{b}	99.7^{b}	54.0^{a}	3.7$_{a}$	1.3^{a}	36.3^{a}	0.4^{a}	0.6^{a}
		C$_{G}$		4.5^{a}	5.8^{a}	17.6^{a}	115.3^{a}	733.3^{a}	123.9^{a}	58.6^{a}	4.3^{a}	1.3^{a}	35.1^{a}	0.4^{a}	0.7^{a}
	Sep 2016	C$_{E}$		4.3^{a}	5.6^{a}	25.9^{a}	90.3^{a}	637.2^{a}	80.1^{b}	45.6^{a}	7.2^{a}	1.5^{a}	51.0^{a}	0.8^{a}	0.7^{b}
		C$_{G}$		4.7^{a}	5.6^{a}	14.2^{a}	107.5^{a}	688.0^{a}	108.2^{a}	49.8^{a}	6.5^{a}	1.2^{a}	39.9^{a}	0.8^{a}	0.9^{a}
	Feb 2017	C$_{E}$		5.4^{a}	5.3^{b}	49.7^{a}	133.5^{a}	795.2^{a}	97.7^{b}	39.4^{a}	11.6^{a}	2.5^{a}	100.0^{a}	0.4^{a}	0.6^{b}
		C$_{G}$		5.2^{a}	5.6^{a}	29.3^{a}	150.5^{a}	902.6^{a}	133.6^{a}	46.6^{a}	9.2^{a}	2.2^{a}	72.0^{a}	0.6^{a}	0.8^{a}
	Sep 2017	C$_{E}$		4.7^{a}	5.4^{a}	12.5^{a}	108.2^{a}	610.7^{a}	92.6^{b}	55.2^{a}	3.0^{a}	1.8^{a}	27.8^{a}	0.4^{a}	0.7^{a}
		C$_{G}$		4.5^{a}	5.7^{a}	7.2^{a}	133.4^{a}	709.2^{a}	124.9^{a}	52.3^{a}	1.8^{a}	1.2^{b}	28.0^{a}	0.4^{a}	0.8^{a}
	Feb 2018	C$_{E}$	1.2^{a}	3.9^{a}	5.6^{a}	22.3^{a}	57.9^{b}	436.3^{b}	65.6^{b}	80.8^{a}	2.4^{a}	6.5^{a}	102.4^{a}	2.7^{a}	1.0^{b}
		C$_{G}$	1.5^{a}	3.8^{a}	5.7^{a}	9.5^{b}	87.0^{a}	508.6^{a}	93.5^{a}	90.2^{a}	2.6^{a}	2.7^{a}	67.5^{b}	2.7^{a}	1.2^{a}
	Sep 2018	C$_{E}$	0.5^{b}	5.2^{a}	5.8^{a}	16.7^{a}	168.3^{a}	1127.8^{a}	121.1^{a}	65.7^{a}	5.1^{a}	1.5^{a}	42.7^{a}	0.8^{a}	1.1^{a}
		C$_{G}$	0.6^{a}	5.5^{a}	5.9^{a}	18.8^{a}	167.9^{a}	1271.3^{a}	140.8^{a}	57.9^{a}	5.0^{a}	1.8^{a}	45.0^{a}	0.9^{a}	1.2^{a}
	Mean	C$_{E}$	0.8^{b}	4.6^{a}	5.6^{b}	24.3^{a}	109.8^{b}	707.9^{b}	92.6^{b}	56.7^{a}	5.5^{a}	2.5^{a}	60.2^{a}	0.9^{a}	0.8^{b}
		C$_{G}$	1.1^{a}	4.7^{a}	5.7^{a}	16.1^{b}	127.1^{a}	802.9^{a}	120.8^{a}	59.3^{a}	4.9^{a}	1.7^{a}	48.1^{b}	1.0^{a}	0.9^{a}
	By soil sampling event														

Depth (m)	Date	Trt	OM (%)	CEC (cmol(+) kg^{-1})	pH	P	K	Ca	Mg	S	Mn	Zn	Fe	Cu	B
						(kg ha^{-1})									
	Feb 2016	C_E		4.0^{b}	5.8^{a}	18.2^{b}	101.2^{bcd}	640.7^{b}	99.7^{ab}	54.0^{bc}	3.7^{b}	1.3^{b}	36.3^{b}	0.4^{c}	0.6^{c}
	Sep 2016			4.3^{b}	5.6^{ab}	25.9^{ab}	90.3^{cd}	637.2^{b}	80.1^{bc}	45.6^{bc}	7.2^{ab}	1.5^{b}	51.0^{b}	0.8^{b}	0.7^{bc}
	Feb 2017			5.4^{a}	5.3^{b}	49.7^{a}	133.5^{ab}	795.2^{b}	97.7^{ab}	39.4^{c}	11.6^{a}	2.5^{b}	100.0^{a}	0.4^{c}	0.6^{c}
	Sep 2017			4.7^{ab}	5.4^{ab}	12.5^{b}	108.2^{bc}	610.7^{bc}	92.6^{abc}	55.2^{bc}	3.0^{b}	1.8^{b}	27.8^{b}	0.4^{c}	0.7^{c}
	Feb 2018		1.2^{a}	3.9^{b}	5.6^{ab}	22.3^{b}	57.9^{d}	436.3^{c}	65.6^{c}	80.8^{a}	2.4^{b}	6.5^{a}	102.4^{a}	2.7^{a}	1.0^{ab}
	Sep 2018		0.5^{b}	5.2^{a}	5.8^{a}	16.7^{b}	168.3^{a}	1127.8^{a}	121.1^{a}	65.7^{ab}	5.1^{b}	1.5^{b}	42.7^{b}	0.8^{b}	1.1^{a}
	Feb 2016	C_G		4.5^{bc}	5.8^{a}	17.6^{ab}	115.3^{bcd}	733.3^{bc}	123.9^{ab}	58.6^{b}	4.3^{bc}	1.3^{bc}	35.1^{c}	0.4^{d}	0.7^{c}
	Sep 2016			4.7^{ab}	5.6^{a}	14.2^{ab}	107.5^{cd}	688.0^{cd}	108.2^{ab}	49.8^{b}	6.5^{ab}	1.2^{c}	39.9^{c}	0.8^{bc}	0.9^{bc}
	Feb 2017			5.2^{ab}	5.6^{a}	29.3^{a}	150.5^{ab}	902.6^{b}	133.6^{ab}	46.6^{b}	9.2^{a}	2.2^{ab}	72.0^{a}	0.6^{cd}	0.8^{c}
	Sep 2017			4.5^{ab}	5.7^{a}	7.2^{b}	133.4^{abc}	709.2^{c}	124.9^{ab}	52.5^{b}	1.8^{c}	1.2^{c}	28.0^{c}	0.4^{d}	0.8^{c}
	Feb 2018		1.5^{a}	3.8^{c}	5.7^{a}	9.5^{b}	87.0^{d}	508.6^{d}	93.5^{b}	90.2^{a}	2.6^{bc}	2.7^{a}	67.5^{ab}	2.7^{a}	1.2^{a}
	Sep 2018		0.6^{b}	5.5^{a}	5.9^{a}	18.8^{ab}	167.9^{a}	1271.3^{a}	140.8^{a}	57.9^{b}	5.0^{abc}	1.8^{abc}	45.0^{bc}	0.9^{b}	1.2^{ab}
0.45-0.6	By fertilization treatment														
	Feb 2016	C_E		5.0^{a}	5.1^{a}	5.7^{a}	73.5^{a}	575.1^{a}	104.7^{a}	77.7^{a}	2.2^{a}	1.4^{a}	23.8^{a}	0.3^{a}	0.7^{a}
		C_G		5.0^{a}	5.3^{a}	4.1^{a}	83.6^{a}	622.1^{a}	115.7^{a}	83.2^{a}	1.8^{a}	1.1^{a}	19.7^{a}	0.3^{a}	0.7^{a}
	Sep 2016	C_E		4.6^{b}	5.3^{a}	9.3^{a}	66.1^{a}	549.3^{a}	86.0^{b}	74.9^{a}	4.2^{a}	0.6^{a}	26.9^{a}	0.4^{a}	0.6^{b}
		C_G		5.4^{a}	5.0^{a}	3.6^{b}	81.3^{a}	646.1^{a}	119.9^{a}	86.0^{a}	2.5^{a}	0.6^{a}	26.9^{a}	0.6^{a}	0.8^{a}
	Feb 2017	C_E		5.5^{b}	4.9^{a}	12.2^{a}	87.4^{b}	684.8^{b}	105.8^{b}	65.9^{a}	4.1^{a}	1.4^{a}	56.7^{a}	0.3^{a}	0.6^{b}
		C_G		5.9^{a}	5.1^{a}	5.7^{b}	114.5^{a}	815.8^{a}	145.9^{a}	74.8^{a}	2.9^{a}	1.4^{a}	35.8^{b}	0.4^{a}	0.8^{a}
	Sep 2017	C_E		4.9^{a}	5.1^{a}	5.8^{a}	73.7^{a}	572.6^{a}	94.6^{a}	46.9^{a}	2.9^{a}	1.3^{a}	20.3^{a}	0.4^{a}	0.6^{a}
		C_G		5.3^{a}	5.1^{a}	3.5^{a}	74.2^{a}	589.0^{a}	110.7^{a}	51.7^{a}	2.6^{a}	1.2^{a}	16.3^{a}	0.3^{a}	0.6^{a}
	Feb 2018	C_E	1.4^{a}	5.3^{a}	5.0^{a}	21.0^{a}	55.3^{a}	507.8^{a}	136.4^{a}	71.2^{a}	7.8^{a}	3.4^{a}	75.4^{a}	2.1^{a}	1.2^{a}
		C_G	1.4^{a}	5.5^{a}	5.1^{a}	15.1^{a}	72.9^{a}	616.0^{a}	176.7^{a}	87.7^{a}	10.2^{a}	6.9^{a}	60.3^{a}	2.1^{a}	1.3^{a}
	Sep 2018	C_E	0.3^{a}	5.2^{a}	5.3^{a}	7.2^{a}	99.1^{a}	799.4^{a}	107.5^{b}	56.5^{a}	2.8^{a}	1.4^{a}	28.7^{a}	0.6^{a}	1.0^{a}
		C_G	0.4^{a}	5.7^{a}	5.3^{a}	7.0^{a}	114.4^{a}	924.1^{a}	136.0^{a}	51.6^{a}	3.2^{a}	1.5^{a}	26.5^{a}	0.6^{a}	1.0^{a}
	Mean	C_E	0.8^{a}	5.1^{b}	5.1^{a}	10.2^{a}	75.8^{b}	614.6^{b}	105.6^{b}	65.5^{a}	4.0^{a}	1.6^{a}	38.7^{a}	0.7^{a}	0.8^{a}
		C_G	0.9^{a}	5.5^{a}	5.2^{a}	6.5^{b}	90.2^{a}	703.0^{a}	134.3^{a}	72.4^{a}	3.9^{a}	2.1^{a}	31.0^{a}	0.7^{a}	0.9^{a}
	By soil sampling event														

Depth (m)	Date	Trt	OM (%)	CEC (cmol(+) kg^{-1})	pH	P	K	Ca	Mg	S	Mn	Zn	Fe	Cu	B
						(kg ha^{-1})									
	Feb 2016	C_E		5.0^{ab}	5.1^{a}	5.7^{b}	73.5^{abc}	575.1^{b}	104.7^{a}	77.7^{a}	2.2^{b}	1.4^{b}	23.8^{b}	0.3^{b}	0.7^{b}
	Sep 2016			4.6^{b}	5.3^{a}	9.3^{ab}	66.1^{bc}	549.3^{b}	86.0^{a}	74.9^{a}	2.8^{b}	0.6^{b}	26.9^{b}	0.4^{b}	0.6^{b}
	Feb 2017			5.5^{a}	4.9^{a}	12.2^{ab}	87.4^{ab}	684.8^{ab}	105.8^{a}	65.9^{ab}	4.1^{ab}	1.4^{b}	56.7^{a}	0.3^{b}	0.6^{b}
	Sep 2017			4.9^{ab}	5.1^{a}	5.8^{b}	73.7^{abc}	572.6^{b}	94.6^{a}	46.9^{b}	2.9^{b}	1.3^{b}	20.3^{b}	0.4^{b}	0.6^{b}
	Feb 2018		1.4^{a}	5.3^{ab}	5.0^{a}	21.0^{a}	55.3^{c}	507.8^{b}	136.4^{a}	71.2^{ab}	7.8^{a}	3.4^{a}	75.4^{a}	2.1^{a}	1.2^{a}
	Sep 2018		0.3^{b}	5.2^{ab}	5.3^{a}	7.2^{b}	99.1^{a}	799.4^{a}	107.5^{a}	56.5^{ab}	4.2^{ab}	1.4^{b}	28.7^{b}	0.6^{b}	1.0^{ab}
	Feb 2016	C_G		5.0^{b}	5.3^{a}	4.1^{b}	83.6^{ab}	622.1^{bc}	115.7^{ab}	83.2^{a}	1.8^{b}	1.1^{b}	19.7^{c}	0.3^{d}	0.7^{bc}
	Sep 2016			5.4^{ab}	5.0^{a}	3.6^{b}	81.3^{b}	646.1^{bc}	119.9^{ab}	86.0^{a}	2.5^{b}	0.6^{b}	26.9^{bc}	0.6^{bc}	0.8^{bc}
	Feb 2017			5.9^{a}	5.1^{a}	5.7^{b}	114.5^{a}	815.8^{ab}	145.9^{ab}	74.8^{ab}	2.9^{b}	1.4^{b}	35.8^{b}	0.4^{cd}	0.8^{bc}
	Sep 2017			5.3^{ab}	5.1^{a}	3.5^{b}	74.2^{b}	589.0^{c}	110.7^{b}	51.7^{b}	2.6^{b}	1.2^{b}	16.3^{c}	0.3^{d}	0.6^{c}
	Feb 2018		1.4^{a}	5.5^{ab}	5.1^{a}	15.1^{a}	72.9^{b}	616.0^{c}	176.7^{a}	87.7^{a}	10.2^{a}	6.7^{a}	60.3^{a}	2.1^{a}	1.3^{a}
	Sep 2018		0.4^{b}	5.7^{ab}	5.3^{a}	7.0^{b}	114.4^{a}	924.1^{a}	136.0^{ab}	51.6^{b}	3.2^{b}	1.5^{b}	26.5^{bc}	0.6^{b}	1.0^{ab}
0.6-0.75	By fertilization treatment														
	Feb 2016	C_E		5.9^{a}	4.9^{a}	12.9^{a}	68.2^{a}	745.5^{a}	135.9^{a}	67.0^{a}	3.7^{a}	1.4^{a}	37.5^{a}	0.4^{a}	0.9^{a}
		C_G		6.2^{a}	5.0^{a}	15.3^{a}	84.6^{a}	876.8^{a}	174.9^{a}	77.2^{a}	4.7^{a}	1.6^{a}	35.9^{a}	0.4^{a}	1.0^{a}
	Sep 2016	C_E		5.1^{a}	4.8^{a}	3.8^{a}	54.9^{a}	515.6^{a}	90.6^{a}	80.6^{a}	1.3^{a}	0.1^{a}	24.0^{a}	0.1^{b}	0.3^{a}
		C_G		5.1^{a}	4.7^{a}	1.7^{a}	53.5^{a}	493.9^{a}	98.4^{a}	88.3^{a}	1.5^{a}	0.1^{a}	15.7^{b}	0.2^{a}	0.3^{a}
	Feb 2017	C_E		5.5^{b}	4.8^{a}	8.6^{a}	71.6^{a}	657.4^{b}	109.4^{b}	142.8^{a}	3.4^{a}	1.3^{a}	48.5^{a}	0.3^{a}	0.5^{a}
		C_G		5.9^{a}	4.8^{a}	5.5^{a}	79.6^{a}	740.2^{a}	142.2^{a}	145.7^{a}	2.2^{a}	1.1^{a}	34.7^{b}	0.4^{a}	0.5^{a}
	Sep 2017	C_E		5.1^{a}	4.6^{a}	4.3^{a}	51.0^{a}	512.6^{a}	92.3^{a}	N/A	3.3^{a}	1.2^{a}	14.9^{a}	0.2^{b}	0.4^{a}
		C_G		5.3^{a}	4.6^{a}	2.8^{a}	57.0^{a}	546.8^{a}	101.8^{a}	N/A	2.9^{a}	1.1^{a}	11.5^{a}	0.3^{a}	0.4^{a}
	Feb 2018	C_E	1.3^{a}	5.8^{a}	4.7^{a}	27.1^{a}	127.6^{a}	542.5^{a}	197.3^{a}	77.0^{a}	6.6^{a}	3.6^{b}	46.6^{a}	0.8^{a}	1.1^{a}
		C_G	1.3^{a}	6.2^{a}	4.7^{a}	21.7^{a}	119.8^{a}	655.5^{a}	285.2^{a}	86.6^{a}	5.4^{a}	7.2^{a}	46.5^{a}	0.9^{a}	1.2^{a}
	Sep 2018	C_E	0.3^{a}	5.1^{a}	5.0^{a}	4.6^{a}	66.1^{a}	510.8^{a}	96.2^{b}	54.6^{a}	2.0^{a}	1.3^{a}	18.8^{a}	0.5^{a}	0.5^{a}
		C_G	0.3^{a}	5.3^{a}	4.9^{a}	5.7^{a}	74.2^{a}	599.2^{a}	125.1^{a}	49.0^{b}	1.7^{a}	1.3^{a}	18.8^{a}	0.6^{a}	0.6^{a}
	Mean	C_E	0.7^{a}	5.4^{b}	4.8^{a}	10.1^{a}	73.1^{a}	574.5^{b}	119.8^{b}	70.5^{a}	3.4^{a}	1.5^{a}	31.6^{a}	0.4^{a}	0.6^{a}
		C_G	0.8^{a}	5.7^{a}	4.8^{a}	8.7^{a}	78.0^{a}	653.3^{a}	154.4^{a}	74.4^{a}	3.1^{a}	2.1^{a}	27.1^{a}	0.4^{a}	0.7^{a}
	By soil sampling event														

Depth (m)	**Date**	**Trt**	**OM (%)**	**CEC (cmol(+) kg^{-1})**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Mn**	**Zn**	**Fe**	**Cu**	**B**
						(kg ha^{-1})									
	Feb 2016	C_E		5.9^{a}	4.9^{ab}	12.9^{a}	68.2^{b}	745.5^{a}	135.9^{b}	67.0^{b}	3.7^{ab}	1.4^{b}	37.5^{ab}	0.4^{bc}	0.9^{a}
	Sep 2016			5.1^{b}	4.8^{ab}	3.8^{b}	54.9^{b}	493.9^{b}	90.6^{b}	80.6^{b}	1.3^{b}	0.1^{c}	24.0^{bc}	0.1^{d}	0.3^{b}
	Feb 2017			5.5^{ab}	4.8^{ab}	8.6^{b}	71.6^{b}	657.4^{ab}	109.4^{b}	142.8^{a}	3.4^{ab}	1.3^{b}	48.5^{a}	0.3^{bcd}	0.5^{b}
	Sep 2017			5.1^{b}	4.6^{b}	4.3^{b}	51.0^{b}	512.6^{b}	92.3^{b}		3.3^{ab}	1.2^{b}	14.9^{c}	0.2^{cd}	0.4^{b}
	Feb 2018		1.3^{a}	5.8^{a}	4.7^{ab}	27.1^{a}	127.6^{a}	542.5^{b}	197.3^{a}	77.0^{b}	6.6^{a}	3.6^{a}	46.6^{a}	0.8^{a}	1.1^{a}
	Sep 2018		0.3^{b}	5.1^{b}	5.0^{a}	4.6^{b}	66.1^{b}	510.8^{b}	96.2^{b}	54.6^{b}	2.0^{b}	1.3^{b}	18.8^{bc}	0.5^{b}	0.5^{b}
	Feb 2016	C_G		6.2^{a}	5.0^{a}	15.3^{b}	84.6^{ab}	876.8^{a}	174.9^{b}	77.2^{b}	4.7^{ab}	1.6^{b}	35.9^{a}	0.4^{c}	1.0^{a}
	Sep 2016			5.1^{c}	4.7^{a}	1.7^{c}	53.5^{b}	515.6^{c}	98.4^{c}	88.3^{b}	1.5^{c}	0.1^{b}	15.7^{b}	0.2^{c}	0.3^{c}
	Feb 2017			5.9^{ab}	4.8^{a}	5.5^{c}	79.6^{b}	740.2^{ab}	142.2^{bc}	145.7^{a}	2.2^{bc}	1.1^{b}	34.8^{a}	0.4^{c}	0.5^{bc}
	Sep 2017			5.3^{bc}	4.6^{a}	2.8^{c}	57.0^{b}	545.8^{c}	101.8^{bc}		2.9^{abc}	1.1^{b}	11.5^{b}	0.3^{c}	0.4^{bc}
	Feb 2018		1.3^{a}	6.2^{a}	4.7^{a}	21.7^{a}	119.8^{a}	655.5^{bc}	285.2^{a}	86.6^{b}	5.4^{a}	7.2^{a}	46.5^{a}	0.9^{a}	1.2^{a}
	Sep 2018		0.3^{b}	5.3^{bc}	4.9^{a}	5.7^{c}	74.2^{b}	599.2^{bc}	125.1^{bc}	49.0^{c}	1.7^{c}	1.3^{b}	18.8^{b}	0.6^{b}	0.6^{b}
By depth															
0-0.15	Mean	Mean	0.8^{bc}	4.9^{b}	6.4^{a}	150.8^{a}	152.6^{a}	1365.3^{a}	165.4^{a}	51.9^{bc}	22.0^{a}	10.8^{a}	92.3^{a}	3.5^{a}	0.6^{b}
0.15-0.3			0.7^{c}	4.4^{c}	6.0^{b}	103.9^{b}	123.7^{b}	953.2^{b}	115.0^{c}	47.5^{c}	17.3^{b}	6.7^{b}	102.9^{a}	3.2^{a}	0.6^{b}
0.3-0.45			1.0^{a}	4.7^{bc}	5.6^{c}	20.2^{c}	118.4^{b}	755.2^{c}	106.6^{c}	58.0^{b}	5.2^{c}	2.1^{c}	54.2^{b}	0.9^{b}	0.9^{a}
0.45-0.6			0.9^{ab}	5.3^{a}	5.1^{d}	8.4^{c}	82.9^{c}	658.6^{cd}	119.9^{bc}	68.9^{a}	4.0^{c}	1.8^{c}	34.9^{c}	0.7^{b}	0.8^{a}
0.6-0.75			0.8^{abc}	5.5^{a}	4.8^{e}	9.4^{c}	75.6^{c}	613.7^{d}	137.0^{b}	72.4^{a}	3.2^{c}	1.8^{c}	29.3^{c}	0.4^{b}	0.7^{b}

APPENDIX B

PLANT TISSUE ANALYSIS

Mean values of macronutrients and micronutrients concentrations in leaves at various growing stages for each treatment and growing season. Means followed by different letters between fertilization treatments within the same growing season and stage, between fertilization treatments withing the same growing stage, and between growing seasons within the same fertilization treatment and growing stage are significantly different ($p - value < 0.05$).

Growing Stage	**Year**	**Trt**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Mn**	**Fe**	**B**	**Cu**	**Zn**
			(%)						**(ppm)**				
V3	By fertilization treatment												
	2016	C_E	4.3^a	0.8^a	3.7^a	0.6^a	0.2^a	0.2^a	61.9^a	724.5^a	13.9^a	1.5^a	32.5^a
		C_G	4.6^a	0.7^a	4.0^a	0.6^a	0.2^a	0.2^a	61.3^a	581.8^a	10.3^a	2.0^a	32.8^a
	2017	C_E	5.0^a	0.4^a	2.7^a	0.5^a	0.2^a	0.2^a	34.0^a	260.1^a	4.1^a	3.9^a	33.2^a
		C_G	4.7^a	0.3^a	2.6^a	0.5^a	0.1^a	0.2^a	36.7^a	316.4^a	5.7^a	4.8^a	30.5^a
	2018	C_E	4.9^a	0.7^a	4.8^a	0.8^a	0.2^a	0.3^a	68.3^a	308.3^a	14.5^a	4.0^a	58.9^a
		C_G	4.8^a	0.6^a	4.5^a	0.7^a	0.2^b	0.3^a	57.5^a	409.5^a	12.9^a	4.1^a	123.8^a
	Mean	C_E	4.7^a	0.6^a	3.7^a	0.6^a	0.2^a	0.2^a	54.7^a	431.0^a	10.8^a	3.1^a	41.5^a
		C_G	4.7^a	0.6^a	3.7^a	0.6^a	0.2^a	0.2^a	51.8^a	435.9^a	9.6^a	3.6^a	62.4^a
	By growing season												
	2016	C_E	4.3^b	0.8^a	3.7^b	0.6^b	0.2^{ab}	0.2^b	61.9^a	724.5^a	13.9^a	1.5^b	32.5^b
	2017		5.0^a	0.4^b	2.7^c	0.5^c	0.2^b	0.2^b	34.0^b	260.1^b	4.1^b	3.9^a	33.2^b
	2018		4.9^a	0.7^a	4.8^a	0.8^a	0.2^a	0.3^a	68.3^a	308.3^b	14.5^a	4.0^a	58.9^a
	2016	C_G	4.6^a	0.7^a	4.0^a	0.6^b	0.2^a	0.2^b	61.3^a	581.8^a	10.3^a	2.0^b	32.8^b
	2017		4.7^a	0.3^c	2.6^b	0.5^c	0.1^b	0.2^b	36.7^b	316.4^b	5.7^b	4.8^a	30.5^b
	2018		4.8^a	0.6^b	4.5^a	0.7^a	0.2^a	0.3^a	57.5^a	409.5^{ab}	12.9^a	4.1^a	123.8^a

Growing Stage	Year	Trt	N	P	K	Ca	Mg	S	Mn	Fe	B	Cu	Zn
			(%)						(ppm)				
V4	By fertilization treatment												
	2016	C_E	5.3^a	0.8^a	4.9^a	0.8^a	0.3^a	0.2^a	89.4^a	256.1^a	7.8^a	3.9^a	42.2^a
		C_G	5.3^a	0.7^a	5.1^a	0.8^a	0.2^a	0.2^a	79.4^a	261.6^a	7.3^a	4.3^a	39.6^a
	2017	C_E	4.0^b	0.4^a	3.5^b	0.6^a	0.2^a	0.2^a	41.5^a	162.5^a	11.0^a	3.8^a	28.7^a
		C_G	4.5^a	0.4^a	3.9^a	0.5^b	0.2^b	0.2^a	38.5^a	161.3^a	12.2^a	4.2^a	27.4^a
	2018	C_E	5.0^a	0.6^a	4.1^a	0.7^a	0.2^a	0.5^a	50.2^a	286.3^a	14.7^a	3.7^a	64.2^a
		C_G	5.2^a	0.6^a	4.1^a	0.7^a	0.2^a	0.5^a	55.7^a	293.8^a	13.7^a	4.5^a	59.8^a
	Mean	C_E	4.8^a	0.6^a	4.2^a	0.7^a	0.2^a	0.3^a	60.4^a	235^a	11.2^a	3.8^b	45.1^a
		C_G	5.0^a	0.6^a	4.4^a	0.7^a	0.2^a	0.3^a	57.9^a	238.9^a	11.1^a	4.4^a	42.3^a
	By growing season												
	2016	C_E	5.3^a	0.8^a	4.9^a	0.8^a	0.3^a	0.2^b	89.4^a	256.1^{ab}	7.8^c	3.9^a	42.7^b
	2017		4.0^b	0.4^c	3.5^b	0.6^b	0.2^b	0.2^b	41.5^b	162.5^b	11.0^b	3.8^a	28.7^b
	2018		5.0^a	0.6^b	4.1^b	0.7^{ab}	0.2^b	0.5^a	50.2^b	286.3^a	14.7^a	3.7^a	64.2^a
	2016	C_G	5.3^a	0.7^a	5.1^a	0.8^a	0.2^a	0.2^b	79.4^a	261.6^a	7.3^b	4.3^a	39.6^b
	2017		4.5^b	0.4^c	3.9^b	0.5^b	0.2^b	0.2^b	38.5^b	161.3^b	12.2^a	4.2^a	27.4^c
	2018		5.2^a	0.6^b	4.1^b	0.7^a	0.2^b	0.5^a	55.7^b	293.8^a	13.7^a	4.5^a	59.8^a
V5	By fertilization treatment												
	2018	C_E	4.9^a	0.6^a	4.3^b	0.7^a	0.2^a	0.3^a	46.6^a	217.4^a	11.0^a	3.9^a	38.7^a
		C_G	4.8^a	0.6^a	4.8^a	0.5^b	0.2^a	0.3^a	35.0^b	222.3^a	11.6^a	3.9^a	40.3^a
V6	By fertilization treatment												
	2017	C_E	4.4^a	0.3^a	3.1^a	1.0^a	0.2^a	0.3^a	61.1^a	202.1^a	9.3^a	3.9^a	18.1^a
		C_G	4.5^b	0.3^a	3.3^a	0.8^b	0.2^b	0.3^a	54.3^a	183.5^a	9.1^a	4.3^a	21.3^a
	2018	C_E	4.4^a	0.4^a	3.8^a	0.9^a	0.2^a	0.3^a	40.0^a	188.4^a	12.1^a	5.2^a	91.8^a
		C_G	4.5^a	0.4^a	3.9^a	0.9^a	0.2^a	0.3^a	42.9^a	168.8^a	11.6^a	5.3^a	72.1^a
	Mean	C_E	4.4^a	0.3^a	3.5^a	1.0^a	0.2^a	0.3^a	53.6^a	195.3^a	10.7^a	4.5^a	55.0^a
		C_G	4.5^a	0.3^a	3.6^a	0.9^a	0.2^b	0.3^a	48.6^a	176.2^a	10.3^a	4.8^a	46.7^a
	By growing season												
	2017	C_E	4.4^a	0.3^b	3.1^b	1.0^a	0.2^a	0.3^a	67.1^a	202.1^a	9.3^a	3.9^a	18.1^a

Growing Stage	**Year**	**Trt**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Mn**	**Fe**	**B**	**Cu**	**Zn**
			(%)						**(ppm)**				
	2018		4.4^{a}	0.4^{a}	3.9^{a}	0.9^{a}	0.2^{a}	0.3^{a}	40.0^{b}	188.4^{a}	12.1^{a}	5.2^{a}	91.8^{a}
	2017	C_G	4.5^{a}	0.3^{b}	3.3^{b}	0.8^{b}	0.2^{a}	0.3^{b}	54.3^{a}	183.5^{a}	9.1^{a}	4.3^{a}	21.3^{b}
	2018		4.5^{a}	0.4^{a}	3.9^{a}	0.9^{a}	0.2^{a}	0.3^{a}	42.9^{a}	168.8^{a}	11.6^{a}	5.3^{a}	72.1^{a}
V7	By fertilization treatment												
	2016	C_E	5.3^{b}	0.4^{a}	3.4^{a}	1.4^{a}	0.2^{a}	0.3^{b}	243.0^{a}	155.6^{a}	8.4^{a}	13.8^{a}	44.6^{a}
		C_G	5.7^{a}	0.4^{a}	3.3^{a}	1.3^{a}	0.2^{a}	0.4^{a}	217.8^{a}	150.5^{a}	7.7^{a}	14.8^{a}	43.6^{a}
	2017	C_E	5.0^{b}	0.3^{a}	2.5^{b}	0.9^{a}	0.3^{a}	0.3^{a}	73.1^{a}	166.9^{a}	5.3^{a}	7.3^{b}	18.3^{b}
		C_G	5.2^{a}	0.3^{a}	3.0^{a}	0.9^{a}	0.3^{a}	0.3^{a}	79.7^{a}	139.9^{a}	5.8^{a}	10.8^{a}	30.7^{a}
	2018	C_E	3.7^{a}	0.3^{a}	4.1^{a}	0.8^{a}	0.2^{a}	0.2^{a}	32.6^{a}	138.2^{a}	9.0^{a}	6.1^{a}	25.5^{a}
		C_G	3.9^{a}	0.3^{a}	4.1^{a}	0.8^{a}	0.2^{b}	0.2^{a}	34.9^{a}	139.3^{a}	9.6^{a}	6.5^{a}	30.7^{a}
	Mean	C_E	4.7^{a}	0.3^{a}	3.3^{a}	1.0^{a}	0.2^{a}	0.3^{a}	116.2^{a}	153.6^{a}	7.5^{a}	9.1^{a}	29.5^{a}
		C_G	5.0^{a}	0.3^{a}	3.5^{a}	1.0^{a}	0.2^{a}	0.3^{a}	110.8^{a}	143.2^{a}	7.7^{a}	10.7^{a}	35.0^{a}
	By growing season												
	2016	C_E	5.3^{a}	0.4^{a}	3.4^{b}	1.4^{a}	0.2^{b}	0.3^{a}	243.0^{a}	155.6^{a}	8.4^{a}	13.8^{a}	44.6^{a}
	2017		5.0^{b}	0.3^{c}	2.5^{c}	0.9^{b}	0.3^{a}	0.3^{a}	73.1^{b}	166.9^{a}	5.3^{b}	7.3^{b}	18.3^{b}
	2018		3.7^{c}	0.3^{b}	4.0^{a}	0.8^{b}	0.2^{b}	0.2^{b}	32.6^{b}	138.2^{a}	9.0^{a}	6.1^{c}	25.5^{b}
	2016	C_G	5.7^{a}	0.4^{a}	3.3^{b}	1.3^{a}	0.2^{b}	0.4^{a}	217.8^{a}	150.5^{a}	7.7^{ab}	14.8^{a}	43.6^{a}
	2017		5.2^{b}	0.3^{c}	3.0^{c}	0.8^{b}	0.3^{a}	0.3^{b}	79.7^{b}	139.9^{a}	5.8^{b}	10.8^{b}	30.7^{b}
	2018		3.9^{c}	0.3^{b}	4.1^{a}	0.8^{b}	0.2^{b}	0.2^{c}	34.9^{b}	139.3^{a}	9.6^{a}	6.5^{c}	30.7^{b}
V8	By fertilization treatment												
	2018	C_E	3.6^{a}	0.3^{a}	3.7^{a}	0.6^{a}	0.2^{a}	0.2^{a}	26.6^{a}	131.7^{b}	7.0^{a}	5.3^{a}	22.4^{a}
		C_G	3.8^{a}	0.3^{a}	3.6^{a}	0.6^{a}	0.2^{a}	0.2^{a}	29.0^{a}	169.0^{a}	8.6^{a}	5.0^{a}	24.5^{a}
V10	By fertilization treatment												
	2018	C_E	3.8^{a}	0.3^{a}	3.0^{a}	0.8^{a}	0.2^{a}	0.3^{a}	29.1^{a}	184.3^{a}	17.6^{a}	5.0^{a}	35.0^{a}
		C_G	3.8^{a}	0.3^{a}	3.3^{a}	0.7^{a}	0.2^{b}	0.3^{a}	29.2^{a}	241.6^{a}	20.7^{a}	5.3^{a}	35.5^{a}
V12	By fertilization treatment												
	2016	C_E	3.5^{b}	0.4^{a}	2.6^{a}	0.7^{a}	0.2^{a}	0.2^{a}	125.3^{a}	198.1^{a}	8.8^{a}	5.4^{a}	40.2^{a}
		C_G	3.7^{a}	0.4^{a}	2.7^{a}	0.6^{a}	0.2^{a}	0.3^{a}	118.4^{a}	218.4^{a}	9.2^{a}	4.9^{a}	39.7^{a}

Growing Stage	**Year**	**Trt**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Mn**	**Fe**	**B**	**Cu**	**Zn**
			(%)						**(ppm)**				
	2017	C_E	4.1^a	0.3^b	2.7^b	1.5^a	0.3^a	0.3^a	71.7^a	197.7^a	6.9^a	6.7^b	33.3^a
		C_G	4.2^a	0.3^a	3.5^a	1.4^a	0.3^a	0.3^a	79.0^a	217.6^a	7.0^a	9.6^a	35.8^a
	2018	C_E	2.9^a	0.3^a	3.0^a	0.4^b	0.2^a	0.2^b	28.7^a	211.3^a	17.6^a	6.7^a	26.9^a
		C_G	3.1^a	0.3^a	3.3^a	0.4^a	0.2^b	0.3^a	28.4^a	221.8^a	18.8^a	6.5^a	27.5^a
	Mean	C_E	3.5^a	0.3^a	2.8^b	0.8^a	0.2^a	0.3^a	75.2^a	202.3^a	11.1^a	6.3^a	33.5^a
		C_G	3.7^a	0.3^a	3.2^a	0.8^a	0.2^a	0.3^a	75.3^a	219.2^a	11.7^a	7.0^a	34.3^a
	By growing season												
	2016	C_E	3.5^b	0.4^a	2.6^a	0.7^b	0.2^b	0.2^b	125.3^a	198.1^a	8.8^b	5.4^a	40.2^a
	2017		4.1^a	0.3^b	2.7^a	1.5^a	0.3^a	0.3^a	71.7^b	197.7^a	6.9^b	6.7^a	33.3^{ab}
	2018		2.9^c	0.3^b	3.0^a	0.4^c	0.2^b	0.2^b	28.7^c	211.3^a	17.6^a	6.7^a	26.9^b
	2016	C_G	3.7^b	0.4^a	2.7^b	0.6^b	0.2^b	0.3^b	118.4^a	218.4^a	9.2^b	4.9^b	39.7^a
	2017		4.2^a	0.3^a	3.5^a	1.4^a	0.3^a	0.3^a	79.0^a	217.6^a	7.0^b	9.6^a	35.8^{ab}
	2018		3.1^c	0.3^a	3.3^{ab}	0.4^b	0.2^b	0.3^b	28.4^b	221.8^a	18.8^a	6.5^b	27.5^b
V14	By fertilization treatment												
	2018	C_E	3.7^a	0.3^a	2.3^a	0.4^a	0.2^a	0.2^a	30.0^a	131.6^a	17.5^a	5.3^a	66.4^a
		C_G	3.6^a	0.3^a	2.4^a	0.4^a	0.1^a	0.2^a	28.5^a	138.1^a	19.2^a	5.1^a	87.7^a
VT	By fertilization treatment												
	2016	C_E	4.1^a	0.3^a	2.5^a	0.8^a	0.2^a	0.2^a	128.4^a	145.9^a	9.9^a	7.4^a	48.7^a
		C_G	4.1^a	0.4^a	2.6^a	0.7^a	0.2^a	0.2^a	118.1^a	157.3^a	9.3^a	6.6^a	43.9^a
	2017	C_E	3.9^a	0.4^a	2.5^a	0.8^a	0.3^a	0.3^a	78.7^a	245.0^a	8.4^a	8.4^a	38.7^a
		C_G	3.9^a	0.4^a	2.7^a	0.7^a	0.3^a	0.3^a	71.9^a	242.3^a	10.2^a	9.3^a	38.6^a
	2018	C_E	3.3^a	0.4^a	2.6^a	0.4^a	0.2^a	0.2^a	31.7^a	78.8^b	11.3^a	4.2^a	47.4^a
		C_G	3.5^a	0.4^a	2.7^a	0.4^a	0.2^a	0.2^a	30.6^a	105.6^a	14.3^a	4.4^a	56.5^a
	Mean	C_E	3.8^a	0.4^a	2.5^b	0.6^a	0.2^a	0.2^a	79.6^a	156.6^a	9.9^a	6.7^a	44.9^a
		C_G	3.8^a	0.4^a	2.7^a	0.6^a	0.2^a	0.2^a	73.5^a	168.4^a	11.3^a	6.8^a	46.4^a
	By growing season												
	2016	C_E	4.1^a	0.3^b	2.5^a	0.8^a	0.2^b	0.2^b	128.4^a	145.9^b	9.9^a	7.4^a	48.7^a
	2017		3.9^a	0.4^a	2.5^a	0.8^a	0.3^a	0.3^a	78.7^b	245.0^a	8.4^a	8.4^a	38.7^a

Growing Stage	Year	Trt	N	P	K	Ca	Mg	S	Mn	Fe	B	Cu	Zn
			(%)						(ppm)				
	2018		3.3^{b}	0.4^{a}	2.6^{a}	0.4^{b}	0.2^{c}	0.2^{b}	31.7^{c}	78.8^{c}	11.3^{a}	4.2^{b}	47.4^{a}
	2016	C_G	4.1^{a}	0.3^{b}	2.6^{a}	0.7^{a}	0.2^{b}	0.2^{b}	118.1^{a}	157.3^{b}	9.3^{a}	6.6^{b}	43.9^{a}
	2017		3.9^{b}	0.4^{ab}	2.7^{a}	0.7^{a}	0.3^{a}	0.3^{a}	71.9^{b}	242.3^{a}	10.2^{a}	9.3^{a}	38.6^{a}
	2018		3.5^{c}	0.4^{a}	2.7^{a}	0.4^{b}	0.2^{b}	0.2^{b}	30.6^{c}	105.6^{c}	14.3^{a}	4.4^{b}	56.5^{a}
R1	By fertilization treatment												
	2018	C_E	3.2^{a}	0.4^{a}	2.5^{a}	0.6^{a}	0.2^{a}	0.2^{a}	33.5^{a}	103.5^{b}	15.0^{a}	6.3^{a}	34.5^{a}
		C_G	3.1^{a}	0.4^{a}	2.7^{a}	0.5^{b}	0.2^{a}	0.2^{a}	24.7^{a}	130.6^{a}	16.5^{a}	5.4^{a}	37.4^{a}
R2	By fertilization treatment												
	2018	C_E	3.2^{a}	0.4^{a}	2.6^{a}	0.7^{a}	0.2^{a}	0.3^{a}	23.3^{a}	116.7^{a}	10.1^{a}	3.5^{a}	34.6^{a}
		C_G	3.0^{a}	0.4^{a}	2.8^{a}	0.6^{a}	0.2^{b}	0.3^{a}	23.2^{a}	129.4^{a}	11.9^{a}	3.8^{a}	57.7^{a}
R3	By fertilization treatment												
	2016	C_E	3.3^{a}	0.4^{a}	1.5^{a}	0.6^{a}	0.3^{a}	0.2^{a}	232.0^{a}	204.8^{a}	10.6^{a}	12.0^{a}	59.2^{a}
		C_G	3.5^{a}	0.4^{a}	1.6^{a}	0.5^{a}	0.3^{a}	0.2^{a}	217.5^{a}	173.2^{a}	10.3^{a}	12.2^{a}	63.0^{a}
	2017	C_E	3.7^{a}	0.4^{a}	1.8^{a}	0.9^{a}	0.3^{a}	0.2^{a}	91.8^{a}	184.5^{a}	7.6^{a}	9.3^{a}	45.2^{a}
		C_G	3.7^{a}	0.4^{a}	1.9^{a}	0.9^{a}	0.3^{b}	0.2^{a}	98.8^{a}	208.8^{a}	9.5^{a}	10.2^{a}	41.2^{a}
	2018	C_E	2.5^{a}	0.3^{a}	2.2^{a}	0.7^{a}	0.2^{a}	0.2^{a}	20.3^{a}	124.6^{a}	10.5^{b}	6.3^{a}	37.4^{a}
		C_G	2.6^{a}	0.3^{a}	2.3^{a}	0.7^{a}	0.2^{a}	0.2^{a}	28.3^{a}	142.8^{a}	12.9^{a}	5.4^{a}	28.9^{a}
	Mean	C_E	3.2^{a}	0.4^{a}	1.2^{a}	0.7^{a}	0.3^{a}	0.2^{a}	114.7^{a}	171.3^{a}	9.5^{a}	9.2^{a}	47.3^{a}
		C_G	3.3^{a}	0.4^{a}	2.0^{a}	0.7^{a}	0.3^{a}	0.2^{a}	114.9^{a}	174.9^{a}	10.9^{a}	9.2^{a}	44.4^{a}
	By growing season												
	2016	C_E	3.3^{b}	0.4^{b}	1.5^{b}	0.6^{b}	0.3^{a}	0.2^{a}	232.0^{a}	204.8^{a}	10.6^{a}	12.0^{a}	59.2^{a}
	2017		3.7^{a}	0.4^{a}	1.8^{b}	0.9^{a}	0.3^{a}	0.2^{a}	91.8^{b}	184.5^{a}	7.6^{a}	9.3^{b}	45.2^{ab}
	2018		2.5^{c}	0.3^{b}	2.2^{a}	0.7^{b}	0.2^{b}	0.2^{b}	20.3^{c}	124.6^{b}	10.5^{a}	6.3^{c}	37.4^{b}
	2016	C_G	3.5^{a}	0.4^{ab}	1.6^{c}	0.5^{b}	0.3^{a}	0.2^{a}	217.5^{a}	173.2^{a}	10.3^{ab}	12.2^{a}	63.0^{a}
	2017		3.7^{a}	0.4^{a}	1.9^{b}	0.9^{a}	0.3^{a}	0.2^{a}	98.8^{b}	208.8^{a}	9.5^{b}	10.2^{a}	41.2^{b}
	2018		2.6^{b}	0.3^{b}	2.3^{a}	0.7^{ab}	0.2^{b}	0.2^{a}	28.3^{c}	142.8^{a}	12.9^{a}	5.4^{b}	28.9^{b}
R4	By fertilization treatment												
	2016	C_E	3.3^{a}	0.4^{a}	1.4^{b}	0.9^{a}	0.3^{a}	0.2^{a}	194.9^{a}	177.9^{a}	14.7^{a}	11.2^{a}	67.0^{a}

Growing Stage	Year	Trt	N	P	K	Ca	Mg	S	Mn	Fe	B	Cu	Zn
			(%)						(ppm)				
		C_G	3.3^a	0.4^a	1.7^a	0.7^a	0.3^a	0.2^a	173.4^a	151.6^a	11.9^a	10.2^a	58.3^a
	2017	C_E	3.5^b	0.4^a	2.3^a	1.1^a	0.4^a	0.3^a	94.5^a	204.8^a	9.1^b	9.8^a	90.2^a
		C_G	3.7^a	0.3^a	2.0^a	1.0^a	0.3^a	0.2^a	88.8^a	181.9^a	11.2^a	9.5^a	101.6^a
	2018	C_E	2.8^a	0.3^a	2.1^b	0.7^a	0.2^a	0.2^a	24.4^a	128.1^a	15.0^a	5.4^a	65.3^a
		C_G	2.8^a	0.3^a	2.2^a	0.7^a	0.2^a	0.2^a	27.6^a	109.0^a	15.2^a	5.2^a	47.2^a
	Mean	C_E	3.2^a	0.4^a	1.9^a	0.9^a	0.3^a	0.2^a	104.3^a	170.2^a	12.9^a	9.0^a	74.2^a
		C_G	3.3^a	0.4^a	2.0^a	0.8^a	0.3^a	0.2^a	96.6^a	147.5^a	12.7^a	8.3^a	69.0^a
	By growing season												
	2016	C_E	3.3^a	0.4^a	1.4^b	0.9^{ab}	0.3^b	0.2^{ab}	194.9^a	177.9^{ab}	14.7^a	11.2^a	67.0^a
	2017		3.5^a	0.4^a	2.3^a	1.1^a	0.4^a	0.3^a	93.5^b	204.8^a	9.1^b	9.8^a	90.2^a
	2018		2.8^b	0.3^a	2.1^a	0.7^b	0.2^c	0.2^b	24.4^c	128.1^b	15.0^a	5.9^b	65.3^a
	2016	C_G	3.3^b	0.4^a	1.7^b	0.7^b	0.3^a	0.2^{ab}	173.4^a	151.6^{ab}	11.9^a	10.2^a	58.3^b
	2017		3.7^a	0.3^a	2.0^{ab}	1.0^a	0.3^a	0.2^a	88.8^b	181.9^a	11.2^a	9.5^a	101.6^a
	2018		2.8^c	0.3^a	2.2^a	0.7^b	0.2^b	0.2^b	27.6^c	109.0^b	15.2^a	5.2^b	47.2^b
R5	By fertilization treatment												
	2018	C_E	3.0^a	0.4^a	2.0^a	0.7^a	0.2^a	0.2^a	19.1^a	121.7^a	12.1^b	9.4^a	52.0^a
		C_G	3.2^a	0.4^a	2.2^a	0.7^a	0.2^a	0.2^a	23.8^a	162.0^a	14.5^a	10.7^a	53.7^a

APPENDIX C

SOIL CHARACTERISTICS CALCULATED BY DSSAT MODEL

Soil water content at lower limit of plant extractable soil water (LL), soil water content at drained upper limit (DUL), soil water content at saturation (SAT), root growth factor (RGF), saturated hydraulic conductivity (K_S) and bulk density (BD) for each plot and soil depth as calculated by DSSAT model.

Trt	**Plot**	**Depth (m)**	**LL**	**DUL**	**SAT**	**RGF**	**K_S (cm h^{-1})**	**BD (g cm^{-3})**
C_E	W201	0-0.15	0.116	0.196	0.362	1	2.59	1.63
		0.15-0.3	0.1	0.183	0.377	0.638	2.59	1.59
		0.3-0.45	0.125	0.208	0.373	0.468	2.59	1.6
		0.45-0.6	0.15	0.244	0.387	0.343	0.43	1.56
		0.6-0.75	0.142	0.232	0.384	0.254	0.43	1.57
	W202	0-0.15	0.068	0.152	0.398	1	6.11	1.53
		0.15-0.3	0.09	0.17	0.38	0.638	6.11	1.58
		0.3-0.45	0.125	0.21	0.377	0.468	2.59	1.59
		0.45-0.6	0.168	0.257	0.384	0.343	0.43	1.57
		0.6-0.75	0.159	0.248	0.384	0.254	0.43	1.57
	W203	0-0.15	0.066	0.144	0.395	1	6.11	1.54
		0.15-0.3	0.08	0.159	0.384	0.638	6.11	1.57
		0.3-0.45	0.125	0.21	0.377	0.468	2.59	1.59
		0.45-0.6	0.203	0.297	0.387	0.343	0.12	1.56
		0.6-0.75	0.151	0.239	0.384	0.254	0.43	1.57
	W204	0-0.15	0.098	0.185	0.384	1	2.59	1.57
		0.15-0.3	0.076	0.158	0.391	0.638	6.11	1.55
		0.3-0.45	0.078	0.157	0.387	0.468	6.11	1.56
		0.45-0.6	0.08	0.159	0.384	0.343	6.11	1.57
		0.6-0.75	0.08	0.16	0.387	0.254	6.11	1.56
	W205	0-0.15	0.066	0.141	0.398	1	21	1.53
		0.15-0.3	0.07	0.162	0.413	0.638	6.11	1.49
		0.3-0.45	0.125	0.208	0.373	0.468	2.59	1.6
		0.45-0.6	0.161	0.252	0.387	0.343	0.43	1.56
		0.6-0.75	0.153	0.239	0.38	0.254	0.43	1.58
	W206	0-0.15	0.089	0.178	0.391	1	2.59	1.55
		0.15-0.3	0.069	0.155	0.402	0.638	6.11	1.52
		0.3-0.45	0.15	0.235	0.38	0.468	0.43	1.58
		0.45-0.6	0.17	0.259	0.384	0.343	0.43	1.57

Trt	**Plot**	**Depth (m)**	**LL**	**DUL**	**SAT**	**RGF**	**K_S (cm h^{-1})**	**BD (g cm^{-3})**
		0.6-0.75	0.164	0.257	0.387	0.254	0.43	1.56
	E101	0-0.15	0.098	0.182	0.377	1	2.59	1.59
		0.15-0.3	0.098	0.186	0.384	0.638	2.59	1.57
		0.3-0.45	0.103	0.194	0.387	0.468	2.59	1.56
		0.45-0.6	0.152	0.243	0.387	0.343	0.43	1.56
		0.6-0.75	0.152	0.246	0.391	0.254	0.43	1.55
	E102	0-0.15	0.098	0.178	0.373	1	2.59	1.6
		0.15-0.3	0.068	0.152	0.398	0.638	6.11	1.53
		0.3-0.45	0.125	0.222	0.391	0.468	2.59	1.55
		0.45-0.6	0.153	0.239	0.38	0.343	0.43	1.58
		0.6-0.75	0.158	0.244	0.38	0.254	0.43	1.58
	E103	0-0.15	0.079	0.163	0.391	1	6.11	1.55
		0.15-0.3	0.069	0.156	0.402	0.638	6.11	1.52
		0.3-0.45	0.15	0.244	0.387	0.468	0.43	1.56
		0.45-0.6	0.161	0.25	0.384	0.343	0.43	1.57
		0.6-0.75	0.157	0.248	0.387	0.254	0.43	1.56
	E104	0-0.15	0.098	0.178	0.373	1	2.59	1.6
		0.15-0.3	0.107	0.191	0.373	0.638	2.59	1.6
		0.3-0.45	0.127	0.221	0.387	0.468	2.59	1.56
		0.45-0.6	0.116	0.201	0.377	0.343	2.59	1.59
		0.6-0.75	0.133	0.217	0.373	0.254	0.43	1.6
	E301	0-0.15	0.069	0.149	0.391	1	6.11	1.55
		0.15-0.3	0.107	0.197	0.387	0.638	2.59	1.56
		0.3-0.45	0.144	0.236	0.387	0.468	0.43	1.56
		0.45-0.6	0.157	0.252	0.391	0.343	0.43	1.55
		0.6-0.75	0.183	0.275	0.387	0.254	0.43	1.56
	E302	0-0.15	0.109	0.19	0.362	1	2.59	1.63
		0.15-0.3	0.098	0.179	0.373	0.638	2.59	1.6
		0.3-0.45	0.082	0.172	0.398	0.468	2.59	1.53
		0.45-0.6	0.107	0.187	0.366	0.343	2.59	1.62
		0.6-0.75	0.116	0.196	0.366	0.254	2.59	1.62
	E303	0-0.15	0.09	0.175	0.384	1	2.59	1.57
		0.15-0.3	0.107	0.192	0.377	0.638	2.59	1.59
		0.3-0.45	0.16	0.255	0.391	0.468	0.43	1.55
		0.45-0.6	0.157	0.249	0.387	0.343	0.43	1.56
		0.6-0.75	0.166	0.258	0.387	0.254	0.43	1.56
	E304	0-0.15	0.1	0.177	0.373	1	6.11	1.6
		0.15-0.3	0.088	0.166	0.38	0.638	6.11	1.58
		0.3-0.45	0.102	0.185	0.377	0.468	2.59	1.59
		0.45-0.6	0.088	0.166	0.38	0.343	6.11	1.58

Trt	**Plot**	**Depth (m)**	**LL**	**DUL**	**SAT**	**RGF**	**K_S (cm h^{-1})**	**BD (g cm^{-3})**
		0.6-0.75	0.098	0.174	0.373	0.254	6.11	1.6
	E305	0-0.15	0.1	0.191	0.391	1	2.59	1.55
		0.15-0.3	0.107	0.189	0.369	0.638	2.59	1.61
		0.3-0.45	0.133	0.219	0.38	0.468	0.43	1.58
		0.45-0.6	0.192	0.285	0.387	0.343	0.43	1.56
		0.6-0.75	0.166	0.256	0.384	0.254	0.43	1.57
	E306	0-0.15	0.1	0.18	0.373	1	2.59	1.6
		0.15-0.3	0.088	0.163	0.38	0.638	6.11	1.58
		0.3-0.45	0.089	0.175	0.387	0.468	2.59	1.56
		0.45-0.6	0.107	0.185	0.366	0.343	2.59	1.62
		0.6-0.75	0.098	0.174	0.373	0.254	6.11	1.6
C_G	W101	0-0.15	0.078	0.157	0.387	1	6.11	1.56
		0.15-0.3	0.143	0.227	0.377	0.638	0.43	1.59
		0.3-0.45	0.133	0.219	0.38	0.468	0.43	1.58
		0.45-0.6	0.168	0.274	0.398	0.343	0.43	1.53
		0.6-0.75	0.143	0.23	0.38	0.254	0.43	1.58
	W102	0-0.15	0.107	0.197	0.384	1	2.59	1.57
		0.15-0.3	0.109	0.193	0.373	0.638	2.59	1.6
		0.3-0.45	0.125	0.209	0.373	0.468	2.59	1.6
		0.45-0.6	0.161	0.247	0.38	0.343	0.43	1.58
		0.6-0.75	0.151	0.239	0.384	0.254	0.43	1.57
	W103	0-0.15	0.078	0.157	0.387	1	6.11	1.56
		0.15-0.3	0.08	0.159	0.384	0.638	6.11	1.57
		0.3-0.45	0.133	0.22	0.38	0.468	0.43	1.58
		0.45-0.6	0.205	0.307	0.395	0.343	0.12	1.54
		0.6-0.75	0.167	0.26	0.387	0.254	0.43	1.56
	W104	0-0.15	0.089	0.18	0.395	1	2.59	1.54
		0.15-0.3	0.07	0.152	0.395	0.638	6.11	1.54
		0.3-0.45	0.15	0.235	0.38	0.468	0.43	1.58
		0.45-0.6	0.085	0.195	0.427	0.343	2.59	1.45
		0.6-0.75	0.143	0.23	0.38	0.254	0.43	1.58
	W301	0-0.15	0.107	0.192	0.377	1	2.59	1.59
		0.15-0.3	0.098	0.19	0.391	0.638	2.59	1.55
		0.3-0.45	0.142	0.224	0.373	0.468	0.43	1.6
		0.45-0.6	0.17	0.259	0.384	0.343	0.43	1.57
		0.6-0.75	0.192	0.285	0.387	0.254	0.43	1.56
	W302	0-0.15	0.098	0.182	0.377	1	2.59	1.59
		0.15-0.3	0.098	0.182	0.377	0.638	2.59	1.59
		0.3-0.45	0.116	0.202	0.377	0.468	2.59	1.59
		0.45-0.6	0.169	0.259	0.384	0.343	0.43	1.57

Trt	Plot	Depth (m)	LL	DUL	SAT	RGF	K_S (cm h^{-1})	BD (g cm^{-3})
		0.6-0.75	0.183	0.272	0.384	0.254	0.43	1.57
	W303	0-0.15	0.077	0.154	0.387	1	6.11	1.56
		0.15-0.3	0.089	0.178	0.391	0.638	2.59	1.55
		0.3-0.45	0.141	0.228	0.38	0.468	0.43	1.58
		0.45-0.6	0.205	0.302	0.391	0.343	0.12	1.55
		0.6-0.75	0.192	0.279	0.384	0.254	0.43	1.57
	W304	0-0.15	0.107	0.194	0.38	1	2.59	1.58
		0.15-0.3	0.089	0.178	0.391	0.638	2.59	1.55
		0.3-0.45	0.105	0.19	0.377	0.468	2.59	1.59
		0.45-0.6	0.127	0.218	0.384	0.343	2.59	1.57
		0.6-0.75	0.142	0.224	0.373	0.254	0.43	1.6
	W305	0-0.15	0.098	0.179	0.373	1	2.59	1.6
		0.15-0.3	0.089	0.181	0.395	0.638	2.59	1.54
		0.3-0.45	0.15	0.243	0.387	0.468	0.43	1.56
		0.45-0.6	0.196	0.292	0.391	0.343	0.12	1.55
		0.6-0.75	0.201	0.306	0.398	0.254	0.12	1.53
	W306	0-0.15	0.089	0.175	0.387	1	2.59	1.56
		0.15-0.3	0.116	0.204	0.38	0.638	2.59	1.58
		0.3-0.45	0.158	0.256	0.391	0.468	0.43	1.55
		0.45-0.6	0.16	0.255	0.391	0.343	0.43	1.55
		0.6-0.75	0.141	0.228	0.38	0.254	0.43	1.58
	E201	0-0.15	0.098	0.181	0.373	1	2.59	1.6
		0.15-0.3	0.068	0.153	0.398	0.638	6.11	1.53
		0.3-0.45	0.142	0.232	0.384	0.468	0.43	1.57
		0.45-0.6	0.151	0.238	0.38	0.343	0.43	1.58
		0.6-0.75	0.166	0.255	0.384	0.254	0.43	1.57
	E202	0-0.15	0.107	0.188	0.366	1	2.59	1.62
		0.15-0.3	0.098	0.181	0.377	0.638	2.59	1.59
		0.3-0.45	0.091	0.179	0.387	0.468	2.59	1.56
		0.45-0.6	0.126	0.212	0.377	0.343	2.59	1.59
		0.6-0.75	0.133	0.217	0.373	0.254	0.43	1.6
	E203	0-0.15	0.069	0.149	0.391	1	6.11	1.55
		0.15-0.3	0.098	0.183	0.38	0.638	2.59	1.58
		0.3-0.45	0.143	0.232	0.384	0.492	0.43	1.57
		0.45-0.6	0.1	0.21	0.416	0.361	2.59	1.48
		0.6-0.75	0.175	0.265	0.387	0.254	0.43	1.56
	E204	0-0.15	0.107	0.188	0.366	1	2.59	1.62
		0.15-0.3	0.098	0.179	0.373	0.638	2.59	1.6
		0.3-0.45	0.117	0.205	0.38	0.468	2.59	1.58
		0.45-0.6	0.118	0.201	0.369	0.343	2.59	1.61

Trt	**Plot**	**Depth (m)**	**LL**	**DUL**	**SAT**	**RGF**	**K_S (cm h^{-1})**	**BD (g cm^{-3})**
		0.6-0.75	0.134	0.214	0.369	0.254	0.43	1.61
	E205	0-0.15	0.056	0.134	0.405	1	21	1.51
		0.15-0.3	0.047	0.125	0.413	0.638	21	1.49
		0.3-0.45	0.152	0.243	0.387	0.468	0.43	1.56
		0.45-0.6	0.151	0.242	0.387	0.343	0.43	1.56
		0.6-0.75	0.166	0.253	0.38	0.254	0.43	1.58
	E206	0-0.15	0.098	0.173	0.373	1	6.11	1.6
		0.15-0.3	0.098	0.177	0.373	0.638	6.11	1.6
		0.3-0.45	0.063	0.151	0.409	0.468	6.11	1.5
		0.45-0.6	0.068	0.145	0.395	0.343	6.11	1.54
		0.6-0.75	0.098	0.174	0.373	0.254	6.11	1.6