CORN GROWTH AND YIELD RESPONSE TO STARTER FERTILIZER

by

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Dedicated to my family and friends that have been continuously supporting me

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

In previous research in continuous corn with no-till management, starter fertilizer consistently increased vegetative plant development rate and plant dry matter prior to sidedressing and decreased grain moisture. However, increased yield did not always occur. The objective of my study was to evaluate the effects of starter fertilizer on plant dry matter and nutrient content throughout the growing season to determine if differences in these parameters determined early in the growing season persisted throughout reproductive growth and explained yield effects. Experiments were conducted in long-term continuous corn no-tillage fields at SEPAC, NEPAC, and TPAC in 2019 and 2020. At TPAC, treatments were control and starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}. At SEPAC and NEPAC, we also evaluated starter fertilizer composition, and the treatments were control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}. Starter fertilizer was applied 5 cm below and 5 cm to one side of the seed. Total N rate was equalized by adjusting the N application at sidedressing to compensate for the N applied in starter.

Although starter fertilizer treatment effects differed from those of the control, in most cases starter fertilizer effects were the same regardless of composition. Hereafter, ‘starter fertilizer’ will refer to the mean of the three starter fertilizer treatments, N, NP, and NPK for SEPAC and NEPAC or NP in the case of TPAC. Crop growth rate determined by the number of collared leaves was increased by starter fertilizer, compared to the control, at all site-years. Starter fertilizer increased leaf appearance up to one leaf in plots evaluated at the same point in time and final leaf number was also one more leaf per plant. Starter fertilizer increased dry matter as early as V4 compared to the control at SEPAC and TPAC, with differences maximizing around V6-V12. Effects at NEPAC were inconsistent throughout the season. At reproductive stages the magnitude of the differences in dry matter decreased until starter fertilizer and control treatments had similar dry matter at maturity. Before sidedressing, N and P concentrations were greater with starter fertilizer than the control, but after sidedressing concentration of these nutrients were greater with control than starter fertilizer. The differences in N and P concentration between starter treatments and the control increased in later vegetative stages, but decreased during reproductive stages and at maturity. Potassium concentration was generally unaffected by the fertilizer treatments. Plant nutrient content differences between starter fertilizer treatments and the control were similar to differences

seen with dry matter, despite the differences in nutrient concentration between starter fertilizer and the control. When compared at the same growth stage, starter fertilizer treatments and the control, had similar DM and nutrient concentration and content. Starter fertilizer, compared to the control, resulted in earlier silking and/or tasseling at all site-years. Starter fertilizer accelerated vegetative crop development, but this did not result in substantial differences in dry matter or nutrient content at similar growth stages, including physiological maturity. Despite this result, increased grain yield with starter fertilizer, compared to the control, occurred at 3 of 6 site-years and ranged from 300 to 1000 kg ha^{-1}. Grain moisture was decreased by starter fertilizer at 4 of 6 site-years by at least 5 g kg^{-1}.

CHAPTER 1. LITERATURE REVIEW

1.1 Corn production

Corn is the most significant component of the coarse grain trade and an essential crop for food security in the world. It is broadly used to feed livestock, make ethanol and produce human food, beverages, and other industrial uses. In 2018 the total world production was 1099 million Mg with the United States being the largest producer, 366 million Mg (Capehart et al., 2019). In addition to being the largest producer, the United States is also the largest exporter of corn, with 62 thousand tons exported in 2018 to countries including Mexico, Japan, and South Korea (NCGA, 2019). To achieve this level of production, United States farmers plant 37 million hectares, of which 2 million are located in Indiana (Matli, 2019). Growers must adopt different practices like no-tillage management, crop rotations, cover crops, drainage, and irrigation system to take care of the land, improve yields, and have economic revenue that still responds to world population necessities.

1.2 Limiting factors in Corn production

1.2.1 Crop rotation

In Indiana, the usual crop rotations are corn after soybean or corn after corn. The corn-soybean rotation has multiple benefits for farmers and the yield of both crops: it helps control diseases, decreases the need for nitrogen fertilizer for corn, and improves physical soil conditions (Heichel, 1987). Farmers use the corn-corn rotation due to high corn prices. Recently high corn prices were related to the rise in ethanol production and higher grain demand (Stern et al., 2012). Despite the possible economic benefit, planting corn after corn can lead to many problems in the field that can affect plant development, growth, and final yield. One of the most important effects is the yield penalty, a grain yield decrease year after year up to 1250 to 1880 kg ha^{-1} compared to a corn-soybean rotation (Gentry et al., 2013). This yield reduction is frequently associated with crop residues, diseases, pests, and weed management that become more complicated due to the absence of crop rotation.

1.2.2 Tillage system effect

Tillage management is another essential practice that farmers adopt to be more efficient and increase crop yields. There are two main classifications of tillage practices, conventional tillage and conservation tillage. Conservation tillage has been adopted in the past years due to the benefits shown in maintaining and improving soil characteristics. No-tillage or strip-tillage has been shown to retain more organic matter in the soil, increase carbon sequestration, reduce soil erosion and compaction, and decrease the environmental impact of crop production (Busari et al., 2015). However, when using conservation tillage, it is critical to keep in mind some of the possible disadvantages such as a higher accumulation of residues in the field, increased bulk density, decreased soil temperature, and higher water content at planting (USDA-NRCS, 2011). An increase in soil bulk density of 0.06 to 0.09 Mg m^{-3} has been reported as a response to no-till management in the first years after establishment (Martino & Shaykewich, 1994). More residue coverage on soil can result in lower temperature and higher moisture in spring when the corn should be planted. Kladivko et al. (1986) reported a decrease up to 3 °C in the soil surface with no-till compared to conventional tillage practices the first four weeks after planting. Due to colder soil, the planting date may be delayed, decreasing the potential yield by up to 20% (Myers and Wiebold, 2013). In addition, an increase in soil water content has also been reported in no-till management due to higher crop residue coverage that limits evapotranspiration (Blanco-Canqui & Ruis, 2018). Increases in soil moisture over the optimum for seed germination, 50% of the available water capacity, can cause uneven emergence and yield losses of 8-10% (Nielsen, 2015). Another fundamental problem with residues is that nitrogen availability can decrease because of the wider carbon to nitrogen (C/N) ratio of residues, reducing nitrogen mineralization (Gentry et al., 2013).

1.2.3 Soil moisture and temperature effect on corn germination

Soil moisture is a crucial factor in seed germination and crop establishment. Seeds need water and oxygen to begin the germination process. Soils need to have some moisture to allow oxygen and water to flow into the seed to start metabolic activity (Benech-Arnold and Sanchez, 2004). Doneen & MacGillivray (1943) evaluated soil moisture levels (14 to 28% by weight or volume) to determine the optimum moisture for seed germination. More than 80% of corn seeds germinated with soil moisture between 16 and 28%. Soil moisture near field capacity is often adequate for seed germination and the emergence of the crop; but excess soil moisture can result in final yield losses between 8 and 10% for corn due to uneven emergence (Nielsen, 2015). Additionally, if soil is too dry seeds do not germinate or seedlings die (Rindels, 1996).

Soil temperature is another critical component for seed germination and crop growth. Soil temperature for seed germination is generally species specific, directly affecting planting date and growers' plans (Benech-Arnold and Sanchez, 2004). For corn, Nielsen (2015) reported soil temperatures around 12.8 °C to be adequate for seed germination. Nafziger (2008) reported the minimum soil temperature for corn germination to be 10 °C. Additionally, he indicated that growers can follow soil temperatures to select the best planting date, delaying planting if soil conditions are not adequate for germination. Soil temperature is also critical for seedling and plant development. Schneider & Gupta (1985) reported time to corn emergence decreased with increased soil temperature, with temperatures of 5-15 °C delaying emergence by 14 to 21 days compared to >25°C, and affecting plant growth population and final yield.

Soil temperature and soil moisture are affected by the amount of residues covering the soil. A higher amount of residues reduces soil temperature and increases moisture affecting the ability to plant early. Consequently, together no-tillage and continuous corn practices can negatively affect corn growth and yield. Under these two specific conditions, farmers may need to implement different practices in crop management to diminish the negative impacts and increase yield.

1.2.4 Nutrient mineralization

Nutrient mineralization and mobility are affected directly by the soil conditions. Macronutrients most often limiting crop production are nitrogen (N), phosphorus (P), and potassium (K). The low temperatures and high moisture can affect N mineralization. Low temperatures can decrease N mineralization rate due to reduced microbial activity. Microbial activity is favored in soils with temperatures >10 °C (Crohn, 2004). In a Wisconsin study, Andraski & Bundy (2008) reported a decrease of 48 kg ha^{-1} NO_3-N when corn residue covered the field. The reduction in N mineralization was related to the colder soil temperature when residues remained on the soil surface and were not incorporated into the soil. In soils with high moisture, the oxygen content available for microbes can be reduced, affecting microbial activity. Curtin et al. (2012) found decreased N and C mineralization rates when soil moisture was higher than 28%.

Another factor affecting the N mineralization rate is the C:N ratio of the residues left on the field. Corn stover has a C:N ratio of 70:1 compared to 20:1 for soybean and alfalfa (Mannering & Griffith, 1985). A higher C:N ratio decreases the decomposition rate, decreasing the amount of rapidly available N. In addition to soil temperature and moisture, N mineralization can be affected by soil physical conditions. In a study evaluating the effect of soil compaction on N mineralization, Breland & Hansen (1996) reported a decrease in total N mineralization by 18% in compacted soils, indicating a possible effect of no-till management in N mineralization.

Phosphorus is an immobile nutrient in the soil, limiting the uptake by plants roots at early growth stages. Phosphorus exists in the soil in organic and inorganic forms, with organic P being 20-60% of total P (Tessen et al., 1994). Organic P must be mineralized and released into the soil solution to be plant available. Phosphorus mineralization is a biological process affected by soil temperature, moisture, compaction, and pH (Prasad & Chackraborty, 2019). Soil P availability increased with increased temperature due to greater microbial activity (Shaw & Cleveland, 2020). Plant P deficiencies when soils are high testing P are more likely to occur in cold temperatures (Chackraborty & Prasad, 2019). Thus, no-tillage management and residues left in the field can affect the availability of P due to the effect on soil temperature and microbial activity.

Potassium is considered an immobile nutrient in the soil. Potassium is found as a component of soil minerals. Only about 2% of the total K in the soil is available for plant uptake in the soil solution (Martin & Sparks, 1985). Potassium availability is affected by soil moisture, compaction, pH, clay content, and degradation of soil minerals. Potassium uptake is also dependent on the amount of root growth; thus, any stress (low temperature, low soil moisture, soil compaction) limiting root development can decrease K uptake affecting plant development and show K deficiency symptoms. An option to increase K availability in the soil solution is to use species of bacteria that mineralized K from the soil minerals, helping to decrease plant deficiency symptoms (Das & Pradhan, 2016; Sun et al., 2020).

1.3 Starter fertilizer

Starter fertilizer is a practice used to mitigate some adverse effects of continuous corn and no-tillage practices. Starter fertilizer is defined as a "small quantity of fertilizer applied near the seed at planting" (Beegle et al., 2007). Starter fertilizer can be applied as a liquid or solid fertilizer, as a single nutrient or a combination of nutrients. Starter fertilizer can have different placements depending on the equipment that the grower has. The most common placements are 5x5 cm and in-furrow (pop-up). 5x5 refers to the fertilizer applied 5 cm below the seed and 5 cm to one side of the seed, and in-furrow the fertilizer applied directly over the seed (Kaiser & Rubin, 2013). When growers do not have access to the equipment to place fertilizer in the soil, another option is to apply starter fertilizer in a broadcast way; which is less expensive and faster way to apply fertilizer. There are many nutrient combinations used as starter fertilizer, but most supply N and P (Beegle, 2007).

1.3.1 Starter fertilizer benefits

The goal of placing nutrients close to the seed is to encourage contact between the roots and fertilizer soon after germination to provide early nutrient access and enhance crop growth. Some of the benefits of starter fertilizers include increased early season plant growth, increases in dry matter accumulation, and lower grain moisture content at harvest (Vetsch and Randall, 2002). Enhanced early crop growth as an increase in dry matter and increase in plant height is a usual response to starter fertilizer (Bermudez & Mallarino, 2002; Bullock et al., 1993). Nutrient availability is also a benefit of starter fertilizer application. In soils with a higher amount of residues, soils tend to be cooler and wetter, decreasing N, P and S mineralization (Andraski & Bundy, 2008). The application of starter fertilizer enhances early access to nutrients by the corn seedling.

An increase in early season growth can translate into more robust and bigger plants which can help to reduce diseases and insect problems. Another benefit of starter fertilizer is the reduction of days needed to reach reproductive stages, silking, and/or tasseling (Cromley et al., 2006; Kaiser et al., 2016). Reaching reproductive stages faster can result in decreased grain moisture at harvest. In another study evaluating placement and rate of starter fertilizer, Hornaday (2017) reported decreased grain moisture by 11 g kg^{-1} at 9 out of 10 locations. In a study evaluating 5x5 cm and pop-up starter fertilizer Lee (2020) reported a decrease in grain harvest moisture at 4 of 5 locations across Indiana.

In the case of yield, results have been variable. In some cases, starter fertilizer increases yield, but in many others, there is no yield response. Bly et al. (2019) reported an increase in yield when P fertilizer was applied. Bermudez & Mallarino (2004) reported small and infrequent yield responses when starter fertilizer was applied, regardless of the tillage system. In Indiana, Hornaday

(2017) reported an increase in yield only at 4 of 10 location years with the use of starter fertilizer. Additionally, Lee (2020), reported no effects of starter fertilizer in yield at any of the 5 Indiana locations. Even when early-season corn growth is reported as a response to starter fertilizer, yield increases are not always found, indicating early growth is not directly correlated with final yield (Bullock et al., 1993; Mallarino et al., 2011).

1.3.2 Starter fertilizer disadvantages

Applying fertilizer close to the seed can cause problems related to salt, ammonia damage, and change in pH of the germination zone reducing germination and damaging seedlings. Depending on the fertilizer placement and type, the damaging rate can vary. Increasing the distance of fertilizer placement from the seed allows higher rates of fertilizer before reducing germination and seedling development (Hergert et al., 2012). Beegle (2007) recommended no more than 11.2 kg ha^{-1} of N plus K_2O and avoidance of urea or DAP when applying pop-up starter fertilizer. Starter rates placed 5x5 cm from the seed should not be higher than 78 kg ha^{-1} of N plus K_2O (add citation). Phosphorus applied in most fertilizers is not usually considered to be damaging, thus there are no limits on how much P_2O_5 can be applied in 2x2 placement. Additionally, using 5x5 cm fertilizer placement requires a higher investment in equipment than in-furrow placement, increasing production costs (Isleib, 2016). Another issue with high rates of fertilizer application are the additional time spent handling the fertilizer which can slow planting, indirectly affecting crop yield by delaying planting (Nafziger, 2008).

1.3.3 Starter fertilizer placements and formulation

Placement of starter fertilizer is an important factor in deciding what type of fertilizer to use to obtain the most benefit of the nutrients. Starter fertilizer can be applied in different ways, different distances below and to one side or both sides of the planted row, and in-furrow (pop-up). The idea behind the starter fertilizer placement is to place nutrients close to the seed, improving plant emergence and establishment (Brouder, 1996). Starter fertilizer placement in corn has been evaluated historically to see the effect on grain yield and crop characteristics. Bordoli and Mallarino (1998) evaluated different rates of K and P, applied as a 5x5 cm starter, deep banded and as broadcast. In this study there was no interaction effects of placement and rates. Phosphorus placement did not affect yield at any site, but K applied in a deep band increased yield in two sites with high K soil tests. The results were related to weather conditions and soil moisture. In a study across Indiana sites, in-furrow and starter (5x5 cm) were evaluated in continuous corn. The starter treatments increased yield at 4 of 10 locations, while the in-furrow treatment only increased yield at one location, with the 5x5 cm starter having the greater increase in yield (Hornaday, 2017). Another study evaluating broadcast fertilizer and starter (5x5 cm) in cotton reported an increase in plant population by 15% and accelerated flower production by 3 to 4 days with starter fertilizer (Guthrie, 1991). In a Kansas study evaluating 5x5 cm and in-furrow starter application, results indicated that the best placement was 5x5 cm for plant stand, 75000 plants ha^{-1}, while the in-furrow starter decreased plant stand, 62000 plants ha^{-1} (Ruiz Diaz, 2017). In a study evaluating long-term P placement and rate fertilization, the results showed an increase in early P uptake, greater ear leaf P concentration with the 10 kg P ha^{-1} rate applied as a 5x5 starter (Preston et al., 2019). Similar results in plant P uptake and P concentration were obtained by Schwab et al. (2006), who additionally reported an increase in corn, wheat, and soybean yield as a response to P as 5x5 starter application. The final decision of where to place fertilizer depends on the amount of fertilizer and the composition. It is recommended to decrease fertilizer rates when applied as in-furrow to avoid seed damage (Beegle, 2007).

Starter composition is also essential when soil temperatures decrease, and moisture levels can affect plant nutrients uptake. Different studies argue about the need to have only N, or P starter or a mix of NPK to obtain yield increases. Different researchers have found that adding both N and P could be the optimum combination to increased corn yield and decrease grain moisture (Kaiser et al., 2016; Vetsch & Randall 2002; Touchton, 1988; Mascagni et al., 2007). Brouder (1996) reported a corn yield increase of 441 kg ha^{-1} in Indiana when N and P were added as starter. The response was associated with improved seedling growth and development. In a study evaluating N rate (34, 67, 101, and 134 kg N ha^{-1}) as 5x5 cm starter fertilizer containing P and K, Niehues et al. (2004) reported an increase in early season growth and yield regardless of N rate. Rates of 34 kg N ha^{-1}, 34 kg P ha^{-1} and 11 kg K ha^{-1} were enough to obtain crop responses. In a study evaluating NP starter fertilizer in corn production, there was a 30% increase in early growth by 30% at low soil P levels (<15ppm) but no yield response (Wortmann et al., 2006).

Tillage management can affect the response to starter fertilizer containing NPK. In a study evaluating different combinations of NPK starter under no-till and conventional tillage, the results showed a 19% increase in yield in the no-till management with NPK starter fertilizer for the three years evaluated, while under conventional tillage yield increased 8% only in one year. The same study reported a more rapid early-season plant growth with the NP and NPK treatments than N alone or the control regardless of the tillage system (Reeves et al., 1986). The benefit of P and K in starter fertilizer can change depending on soil P and K levels. Bermudez & Mallarino (2004) reported that responses to starter fertilizers are most likely where soil test P is low. In contrast, Kaiser et al. (2016) reported increases in yield and decrease grain moisture with NP starter even when the soil had higher soil P levels. In contrast, the use of K as a starter was helpful in low K testing soils, increasing early corn growth, and enhancing early P and K uptake (Mallarino et al., 2011). Reid and Stewart (2009) evaluated different starter fertilizer mixtures for corn on soils testing very low in K and reported that including K in a starter fertilizer mixture increased yield even if it was applied in addition to a broadcast K. Applying P and K as starter fertilizer can be used to provide for the replacement of nutrients removed in the grain harvest in addition to enhanced early crop growth (Brouder, 1996).

1.3.4 Soil temperature effects on response to starter fertilizer

Soil temperature can affect the response of corn to starter fertilizer. Low soil temperatures can delay the emergence, decrease dry matter accumulation and slow the crop growth rate. In a study evaluating different soil temperature regimes, results showed that corn emergence was most rapid at higher soil temperature, corn emergence was less than 21 days with soil temperatures of at least 15 °C (Schneider & Gupta, 1985). A higher soil temperature is related to faster plant development, roots, and above-ground dry matter accumulation. A study evaluating plant growth and P uptake showed that plants grown at 18 °C accumulated 1.18 g less dry matter and uptake 8.9 mg P pot $^{-1}$ less than plants growth at 25 °C; results were related to lesser root development (Mackay & Barber, 1984). Other effects of colder and wet soils are related to the nutrient content. In nitrogen with colder soils, lower mineralization rates can decrease N availability for the plant at early growth stages (Vigil and Kissel, 1995). In a study evaluating N uptake as affected by soil temperature, Dong et al. (2001) detected an increase in N uptake as soil temperature increased (>12 °C). In the case of K, low soil temperature affects both the ability of the plant to take up K and the amount of available K in the soil. A study evaluating temperature influence on K uptake Claassen & Barber (1976) found that K uptake was more affected in low K testing soils due to lower diffusion at lower soil temperatures. Increased soil temperature generated an increase in metabolic activity and greater development of lateral roots that helped to increase early nutrient uptake. The optimum soil temperature for root elongation in corn is 30 °C (Blacklow, 1972).

1.3.5 Soil moisture effects on response to starter fertilizer

Soil moisture directly affects plant growth and the diffusion of nutrients in the soil. In a study evaluating different soil moisture regimens, 100%, 75%, 50%, and 25% of soil water holding capacity, plant height, leaf area, shoot diameter, and dry weight were maximized at 75% water holding capacity (Chadha et al., 2019). The ideal soil moisture for seed germination was 1.2 times the wilting point water content (changes with soil characteristics). If moisture levels were lower, seed germination was affected, and the seed could die. Additionally, moisture has been related to increasing crop development growth, with higher vegetative growth rates when soil is kept moist (Veihmeyer & Hendrickson, 1950). In a study evaluating shoot dry matter at moisture levels of 70, 40, and 10% soil field capacity in wetting and drying regimens, the results showed that the maximum dry matter was obtained at 40% field capacity, having 2.5 g and 1.0 g more dry matter than the 10% and 70% treatments (Anderson & Kemper, 1964).

Moisture is a key factor in nutrient diffusion to the root system. Phosphorus diffusion is assumed to be the main mechanism of P transport in soils (Barber, 1995). In a study evaluating the effects of soil characteristics on soil P diffusion, Bhadoria et al. (1991) reported a linear increase in P diffusion coefficient with an increase in soil water volumetric content. Potassium is also affected by soil moisture. Zeng & Brown (2000) evaluated K mobility and uptake by corn under different soil moisture regimens. The results showed increased K mobility with increasing soil moisture content, suggesting that more K diffused and was available to plant roots with higher soil water content. The authors evaluated dry-wet periods and reported an increase in K fixation, K mobility, and reduced availability with alternating dry-wet. The study concluded that constant moisture levels enhanced K diffusion to the roots while drying cycles increase K fixation to soil colloids. This study's results are similar to those reported by Schaff & Skogley (1982), who reported increased K concentration with soil moisture levels >17%. In the case of N, soil moisture plays an important role in N mineralization. Cassman & Munns (1980) studied the interaction of four temperature (15, 20, 25, and 30°C) and six moisture levels (0.1, 0.3, 0.7, 2, 4, and 10 bars) on N mineralization. The results showed a significant interaction effect of temperature and moisture, with 30 °C increasing N mineralization at suboptimal soil moisture levels. Additionally, the authors reported maximum mineralization rate in the 0.3 bars treatment regardless of soil temperature levels. In conclusion, the authors agreed that soil moisture and temperature need to be evaluated together when studying nutrient mineralization in soils.

1.3.6 Soil physical conditions effects on response to starter fertilizer

The response of plant to starter fertilizer can be affected by the soil's physical conditions. No-tillage management can initially increase soil bulk density and soil penetration resistance; conventional tillage can increase soil compaction in the long term. An increase in soil compaction can affect root development, nutrient uptake, water movement, water uptake, nutrient availability, and plant development (Blanco-Canqui & Ruis, 2018). Kladivko et al. (1986) evaluated conventional tillage and conservation tillage practices in seven soils across Indiana. The results showed an increase in soil aggregate stability with reduced tillage, with no-till having water-stable aggregate diameter 1.8 cm greater than those with moldboard plow. Different studies have shown the relationship between tillage practices and starter fertilizers. Wortmann et al. (2006) found that starter application generally increased early growth under a no-tillage system, but yield response was infrequent. They concluded that there was a high probability of obtaining yield responses to the starter if the soil water content was adequate and if P levels were low. Another study by Bermudez & Mallarino (2004) showed that starter fertilizer increased yield at three of the seven locations under the no-tillage system, concluding that the starter impacted yield less under this condition. In a study evaluating tillage and no-tillage conditions, Bundy & Widen (1989) found that starter increases in plant height were most apparent in no-till fields planted in May, but no responses were found in the other tillage systems. In the case of yield, the moldboard tillage plus PK starter fertilizer increased yield at the three years when planted in early dates (April and May). Moreover, a more significant positive economic response was seen more frequently with no-tillage than in conventional tillage (Bundy & Widen, 1989). Wortmann et al. (2006) found similar results in a Nebraska study. The results showed an increase in early plant biomass (1.5 to 33 g) when NP starter fertilizer was applied under a no-till system. Another study evaluated the interaction of four tillage systems and starter fertilizer application. In the first year of the study, starter fertilizer increased plant height with higher responses as tillage intensity decreased. Regardless of tillage system, the authors reported a yield increase of 0.5 Mg ha^{-1} indicating that starter can be effective under different tillage systems (Vetsch & Randall, 2002). Nevertheless, many studies have tried to understand the effect of starter fertilizers under different tillage systems; the results do not show any specific trend indicating that more studies are needed to understand how starter affect plant development for specific tillage systems.

CHAPTER 2. CORN RESPONSE TO STARTER FERTILIZER

2.1 Introduction

Corn is one of the most important crops in The United States, with 366 million Mg produced in 2018. With an increase in population, it is necessary to keep producing corn to respond to the human population's necessities. To increase yields, farmers must adopt practices to be more efficient and obtain economic revenue. Different practices like no-tillage management, crop rotations, cover crops, drainage, and irrigation are implemented in corn production systems to make it more sustainable and increase yields (Myers & Wiebold, 2013). However, it is crucial to know the adverse effects of some practices on early crop growth and yield. Continuous corn and no-tillage management can decrease soil temperature and moisture due to the higher amount of residues left in the soil surface, potentially decreasing seed germination, plant development, and crop yield (Gentry et al., 2013). To mitigate these negative impacts, growers use starter fertilizers to enhance early crop growth and better plant establishment that could increase crop yield.

Starter fertilizer is "a small quantity of fertilizer nutrients applied close to the seed at planting" (Beegle et al., 2007). Starter fertilizers can be dry or liquid, where the formulations vary to include nitrogen, phosphorus, and potassium. Placement is essential to avoid seed damage; generally, the most common placements are 5X5 cm below and one side of the seed (Kaiser and Rubin, 2013). This close placement of nutrients at planting time allows new roots to access nutrients faster without wasting energy. Several research studies have shown that starter fertilizer enhances early crop growth, as dry matter accumulation and plant height (Vetsch and Randall 2002, Mallarino et al., 2011). Early crop growth can translate into faster plant development, less time to reach reproductive stages, and decreased grain moisture at harvest.

In general, lower grain moisture at harvest responds to starter fertilizer due to the plants being in the field for more time after the grain is initiated. In the case of yield, starter fertilizers have inconsistent effects. Yield response can be site specific depending on soil fertility levels and field conditions (Bermudez & Mallarino, 2004). Under some specific conditions like limited tillage, early planting, and cold soils, an increase in yield can occur but is not ensured (Camberato et al., 2016). For this reason, it is essential to continue research with starter fertilizer and to try to understand the effects on corn growth, development, and the components of final yield. The objective of this project was to evaluate the effect of starter fertilizer on crop growth and development as well as yield components in a continuous corn cropping system.

2.2 Materials and Methods

2.2.1 Weather information and growing degree days calculation

Weather information of each site was recorded using available automated weather stations. Daily precipitation and daily temperature were obtained through the Indiana state climate office, https://ag.purdue.edu/indiana-state-climate/. Growing degree days (GDD) were calculated based on Celsius degrees starting at planting, using minimum (Tmin) (≥10°C), maximum (≤30°C) daily air temperatures, and a constant temperature base (Tbase) of 10°C. GDD were calculated as (Tmax + Tmin)]/2 – Tbase, (Gilmore and Rogers, 1958).

2.2.2 Location and treatment description

Experiments were conducted in 2019 and 2020 at three Purdue Agricultural Centers, NEPAC, SEPAC, and TPAC. The fields were in long-term corn monoculture with no-tillage management and the same plot areas were used each year. Location and soil series information are shown in Table 1.

2.2.3 Soil sampling and analysis

Soil samples collected pre-planting prior to treatment application were a composite of 12 2.5 cm diameter cores per plot taken to a depth of 0-20 cm. At SEPAC and TPAC, samples were taken in all plots, but in NEPAC samples were obtained only from replications 1, 3, 5, and 6. Soil samples were air-dried, ground, and analyzed for organic matter (loss of ignition at 360° C), pH (1:1 soil-water), and nutrient concentrations (Mehlich 3 extraction with nutrients quantified by inductively coupled plasma spectroscopy (ICP), conducted by A&L Great Lakes Laboratories, Fort Wayne, IN) (Table 2).

Soil temperature was recorded from the day of planting until the last sampling at all sites except TPAC19. Temperature sensors (EL-USB-1, Lascar Electronics Inc., PA, US) were placed in the planted row at 5 and 13 cm deep. At NEPAC19, sensors were placed in 16 plots distributed in four replications. At SEPAC19, sensors were placed in 8 plots across the four replications. At NEPAC20, sensors were placed in 4 plots of two replications. At SEPAC20, sensors were placed in 4 plots, one for each replication. At TPAC20, sensors were placed in two plots in two replications. In all sites, sensors were placed in at least 1 replication of each treatment evaluated.

2.2.4 Planting information

In 2019, trials were planted 3 June at NEPAC and 4 June at SEPAC and TPAC using commercial 6-row corn planters. The unusually late plantings in 2019 were a result of unusually frequent rainfall events that spring. In 2020, trials were planted 12 May at NEPAC, 26 May at TPAC, and 3 June at SEPAC. The late plantings at TPAC and SEPAC were a consequence of unacceptably wet field conditions prior to planting. Hybrids in both years were Beck's 5113AM and Beck's 5829A4 at NEPAC and TPAC, respectively, while Pioneer brand P1197 (non-GMO) was planted at SEPAC. The target seeding rate was 74,100 seeds ha^{-1} for all trials and was selected based on previous research that documented optimum plant populations throughout Indiana (Nielsen et al., 2019). Herbicides appropriate for the weed species known to exist in each field were applied as necessary to control weeds.

At SEPAC, dry fertilizer was broadcast applied at rates of 41 kg N and 46 kg P ha^{-1} in late-fall 2018, 75 kg K ha^{-1} in spring 2019, and 20 kg N, 22 kg P, and 112 kg K ha^{-1} in February 2020. Lime was applied in February 2020 at a variable rate, averaging 2,056 kg ha^{-1}. At NEPAC, 8.5 kg N, 17 kg P, and 44 kg K ha^{-1} were applied in fall 2018 and, 8 kg N, 16 kg P, and 45 kg K ha^{-1} were applied at fall 2019.

2.2.5 Starter fertilizer treatments

Starter fertilizer treatments were applied with the corn planters, 5 cm below and 5 cm to one side of the seed with knife or coulter injectors with volume controlled by variable speed hydraulic or electric pumps. Treatments at NEPAC and SEPAC were: (control), 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; (N), 34 kg N ha^{-1} and 8 kg S ha^{-1}; (NP), N plus 7.5 kg P ha^{-1}; and (NPK), NP plus 9.5 kg K ha^{-1}. Nutrients were supplied as combinations of ammonium thiosulfate (12-0-0-26S), urea-ammonium nitrate (28-0-0), ammonium polyphosphate (10-14-0), and potassium thiosulfate (0-0-20-17S). Ammonium thiosulfate was applied to all treatments to apply the same amount of S that was applied with potassium thiosulfate in the NPK treatment. Starter fertilizer treatments at TPAC were control and (starter) at 46 kg N ha^{-1} and 18 kg P ha^{-1} (28-0-0 and 10-14-0) in 5 cm by 5 cm placement. Neither treatment contained S.

Treatments were arranged in a randomized complete block design with 7, 6, and 5 replications at NEPAC, SEPAC, and TPAC, respectively. Plots consisted of 12 76-cm wide rows by length of field - 110, 639, and 370 m at NEPAC, SEPAC, and TPAC, respectively. At all sites, treatments were applied to the same plots in consecutive seasons.

At each site, liquid nitrogen fertilizer in the form of urea-ammonium-nitrate (28% N) was injected between each pair of rows about 10 cm deep when plants were ~V6. Applications in 2019 were 10 July at SEPAC, 1 July at NEPAC, and 3 July at TPAC. In 2020 applications were 7 July at SEPAC, 8 June at NEPAC, and 15 June at TPAC. All treatments received the same total N rate that was specific for each site; therefore, control plots received more N in the sidedress application than treatments which had received N in starter fertilizer. The total N rate was 244 kg N ha^{-1} for SEPAC in both years. At NEPAC, total N rate was 282 kg and 263 kg N ha^{-1} in 2019 and 2020, respectively. Total N rate at TPAC was 241 kg N ha^{-1} in both years. The target total amount of N fertilizer applied to each trial was based on previous research that documented optimum nitrogen fertilizer rates for corn throughout Indiana (Camberato and Nielsen, 2019).

2.2.6 Quantifying plant development rate

The average number of collared leaves was determined approximately every 10 days when plants had approximately 4 collared leaves (V4) (except TPAC 2019 which began at V6) until plants had begun to present tassels and extrude silks (R1) at SEPAC and NEPAC in 2019 and all fields in 2020 (Table 3). Seven sets of two rows 2-m long (20 to 26 plants) were designated in each plot shortly after plant emergence for determining collared leaves. The sampling areas were distributed throughout the length of each plot and placed in different rows. At the first sampling date there were seven designated zones that were evaluated. At the end of the season only one zone remained due to destructive sampling for dry matter. The tips of the fifth and tenth leaves were removed when plants reached V5 and V10 so that subsequent vegetative growth stages could be accurately determined as the lower leaves senesced and deteriorated. A simple mathematical average growth stage per area was calculated for statistical analysis. At R1, in a predetermined sample area, the proportion of plants exhibiting a tassel and/or silk, the leaf number subtending the ear, and the total number of leaves per plant were recorded.

2.2.7 Plant sample processing and analyses

Whole plant samples were taken at each sampling and physiological maturity [R6 as defined by Abendroth et al. (2011)] from the two rows flagged after leaf collars were counted at all 2019 sites. Due to a shortage of summer labor in 2020 due to COVID-19 health concerns, whole plant samples were only collected at NEPAC 2020. At each sampling date 20 to 26 plants per plot were cut at the soil surface, dried in a forced-air dryer at 60°C for 3 to 5 days until dry weight stabilized, and weighed.

Dried plant tissue was ground to pass a 2 mm mesh screen. Nitrogen concentration was determined with the Dumas Method (method AOAC 990.03) run on an Elementary Rapid-N cube (Elementar, Hanau, Germany). Determination of P, K, Mg, Ca, S, Na, Fe, Mn, B, Cu, and Zn concentrations was with ICP after microwave acid digestion using nitric acid and peroxide (SW846-3051A) by A&L Great Lakes Laboratories (Fort Wayne, IN) for 2019 samples. For 2020 samples the same analysis was conducted at SureTech Laboratories (Indianapolis, IN) where P, K, Mg, Ca, S, Na, Fe, Mn, B, Cu, and Zn concentrations were determined with ICP (Thermo iCAP 6500, Waltham, MA) after microwave acid digestion using nitric acid (AOAC 2017.02).

Corn ears (20 to 26 per plot) were harvested at R6 from the last of the sample areas designated shortly after planting. The number of rows per ear and kernels per row were counted on each ear to determine the total number of harvestable kernels. Ears were shelled with a single ear corn sheller (Agriculex Inc., Canada). Grain and cob were dried at 60°C until they reached a constant weight. Cob tissue and dry weight were included with the R6 stover dry weight and nutrient analysis. The dry grain was sieved to remove damaged kernels prior to counting 1000 kernels with an Old Mill seed counter (International Marketing and Design Co., TX). The 1000 kernel samples were re-dried at 60°C until they reached a constant weight. Another subsample was taken from the sieved kernels and ground to a fine powder with a Blixer® 3 Series D grinder (Robot Coupe U.S.A., Inc., MS) for nutrient analysis as previously described for plant tissue.

2.2.8 Determining grain yield

The middle six rows of each 12-row field-length plot were mechanically harvested with commercial 6-row (4.5 m wide) combines equipped with GPS-enabled yield monitors (grain yield estimation) and integrated grain moisture sensors. Each location's yield monitor was calibrated on the day of harvest following accepted calibration practices. Data processing was performed using QGIS v3.10 (https://qgis.org) and involved removing data points from the edges of the plots and areas showing poor plant development not related to treatment effects at each field. The remaining spatial yield data was intersected with the underlying spatial plot layer and then all the yield data points for each individual plot were averaged to obtain a single value to represent each plot for statistical analysis.

2.2.9 Statistical Analysis

All the data variables were analyzed by location and, where appropriate, sampling date within a year. A single-factor analysis of variance was performed using the R program version 3.6.2, where the starter treatment was the independent variable. A least significant difference (LSD) test was conducted to make comparisons of treatment means when the F-test was significant (alpha≤0.10). For SEPAC and NEPAC, treatment means for N, NP, and NPK rarely differed as assessed by LSD (alpha≤0.10), thus a single-degree-of-freedom contrast (alpha≤0.10) was used to compare the effect of starter fertilizer (the mean of N, NP, and NPK) vs control.

2.3 Results

2.3.1 Weather conditions and soil temperature

In the growing season of 2019 planting was delayed due to higher precipitation in April and May. April and May's precipitation were above the 30-year average at all sites by 5 mm (Table A-1). In the growing season of June through October, precipitation was near average at NEPAC and TPAC, but SEPAC got more rain in June and less in August compared to the average. The air temperature was similar to the 30-year average through the growing season at all sites.

In 2020 the growing season was dry compared to 2019 and the 30-year average (Table A-1). Only in October was total precipitation higher than the 30-year average. The temperature in the growing season from April to October was similar to the 30-year average at all sites.

Soil temperature was obtained from soil sensors placed at each site. At SEPAC19 soil temperature varied from 17 to 33 ˚C with the highest temperature in June and July and lower temperatures in October (Figure 1). At NEPAC19, soil temperatures varied from 14 to 30 ˚C with the highest temperature in July and lower temperatures in October (Figure 2). At SEPAC20, temperatures varied from 12 to 32 ˚C, with lower temperature in October and higher temperature in July (Figure 3). At NEPAC20, soil temperatures varied from 12 to 30 ˚C, with lower temperatures in early May and October (Figure 4). At TPAC20, soil temperature varied from 12 to 28 ˚C, with lower temperatures in October and higher temperatures in July (Figure 5).

2.3.2 Effect of starter fertilizer on leaf appearance

An increased rate of leaf appearance with starter fertilizer compared to control was detectable at the first sampling date at SEPAC19 (265 GDD) and NEPAC19 (277 GDD) and was consistent at all but one sampling date at SEPAC19 (Table 4, 5). The addition of P or P and K to the N-only starter did not affect the number of collared leaves compared with the N-only starter at most sampling dates at either site. The exception was a slight increase in the number of collared leaves (0.1 to 0.2) at NEPAC19 with NPK compared to the N-only starter at three sampling dates. The difference in collared leaves between starter treatments and the control increased over time, attaining an average maximum difference of 1.6 leaves (13.4 vs. 15.0) at 775 GDD at SEPAC19 and 0.9 leaves (12.3 vs 13.2) at 728 GDD at NEPAC19 (Fig. 1).

In 2020 at both SEPAC and NEPAC, an increase in leaf appearance with starter fertilizer was detectable, but lower in magnitude than in 2019. At SEPAC20, an increase in the number of collared leaves was observed with starter fertilizer compared to the control (Table 6). No difference among the three starter treatments differing in composition was observed at SEPAC20, similar to the results at SEPAC19. The difference in the number of leaves between the control and starter fertilizer treatments increased over time, as occurred in 2019. The maximum difference observed was 0.8 leaves (13.8 vs. 14.6) at 776 GDD. At NEPAC20, the number of collared leaves was affected at only 2 of 5 sampling dates and only by the NPK starter treatment, resulting in only 0.2

more leaves than the control treatment at 517 and 619 GDD (Table 7). Furthermore, there were no differences among treatments at 726 GDD, the last time collared leaves were counted.

At TPAC19, the NP starter fertilizer consistently increased the number of collared leaves at all sampling dates (351-750 GDD) (Table 8). The difference in collared leaves between treatments was similar throughout the vegetative stages, ranging from 0.8 to 1.4 leaves. At TPAC20, the response was similar to TPAC19, where the NP starter increased collared leaves at all sampling dates (Table 9). The difference in collared leaves throughout the vegetative stages ranged from 0.6 to 1.3 leaves at 307 to 717 GDD.

2.3.3 Above-ground dry matter accumulation

Starter fertilizer increased above-ground dry matter at the first sampling date (265 GDD, V4) at SEPAC19 (Table 10). Plants with starter fertilizer averaged 7 kg ha^{-1} (29%) greater dry matter than plants without starter. The addition of P or P and K to the N-only starter did not affect dry matter accumulation compared with the N-only starter at most sampling dates. The difference in dry matter between starter and control treatments increased throughout the vegetative growth period, attaining a difference of 680 kg ha^{-1} (33% increase) at 775 GDD (V13-V15). When plants reached reproductive stages, 854 to 1602 GDD (R1 and R6), the difference in dry matter accumulation between control and starter treatments was 552 and 568 kg ha^{-1} at R1 and R6, respectively, equivalent to 16 and 5% increases in dry matter.

At NEPAC19, differences in the above-ground dry matter between starter treatments and the control were less consistent than at SEPAC19 (Table 11). At 4 of the 7 sampling dates starter treatments differed from the control, with no differences among starter treatments differing in composition. The difference in above-ground dry matter with starter versus the control was greater at 454 and 571 GDD (V6-V9) than at other sampling dates. At these two sampling dates starter treatments had 120 and 220 kg ha^{-1} more dry matter than control treatments, respectively, equivalent to 29 and 23% increases in above-ground dry matter. In reproductive stages, differences between treatments were only detected at R1 (845 GDD), where starter treatments had 13% more above-ground dry matter than the control.

In the 2020 growing season, above-ground dry matter accumulation was measured only at NEPAC20. At the first sampling date (359 GDD), NP starter increased above-ground dry matter 98 kg ha^{-1} (~30%) compared to the mean of the NPK, N, and control treatments (Table 12). There were no other detectable effects of starter treatments on above-ground matter at any of 6 other sampling times.

Compared to the control, starter fertilizer increased dry matter throughout the growing season at TPAC19, although the increase was more pronounced at vegetative than reproductive growth stages (Table 13). In vegetative stages, starter fertilizer nearly doubled the dry matter of the control plots beginning at the first sampling date. At 351 GDD (V4), starter fertilizer had 103 kg ha^{-1} more than the control (207 vs. 104 kg ha^{-1}). The greatest difference in dry matter was observed at the end of the vegetative stages (662 GDD), where the starter had 2112 kg ha^{-1}, compared to the control at only 1419 kg ha^{-1}. At the R1 sampling, the control treatment (3936 kg ha^{-1}) had greater dry matter than the starter treatment (3033 kg ha^{-1}). However, this was probably a result of how the sampling was conducted. When plants started showing tassels (between VT and R1), the starter plots were harvest about ten days before the control plots because the control plots were behind in maturity. Control treatments were harvested later in R1. The differences in dry matter seen during vegetative growth stages did not remain at maturity, with starter and control having similar total dry matter.

2.3.4 Nutrient concentration

Nitrogen concentration in plant tissue at all sites in 2019 was adequate at V4 (>30-40 g N kg^{-1}, Campbell, 2000), even in control treatments. At SEPAC19 and NEPAC19 at ~V4, the control had the lowest N concentration among all treatments, 30.6 and 32.3 g N kg^{-1}, respectively (Tables 14-15). Starter fertilizer treatments significantly increased N concentration in tissue at V4 with mean N concentrations of 38.5 and 39.3 g N kg^{-1} at SEPAC19 and NEPAC19, respectively. There were no effects of starter composition on N concentration prior to sidedressing at approximately V6.

After sidedressing, plant N concentration was higher for the control than for starter fertilizer treatments. Nitrogen sidedressing was applied when plants reached V6 - applications in 2019 were 10 July at SEPAC (458 GDD), 1 July at NEPAC (322 GDD), and 3 July at TPAC (351 GDD). Sidedressing in 2020 was 8 June at NEPAC (248 GDD). The total N rate was adjusted to be the same for all the treatments. Thus, control plots received 30 kg N ha^{-1} more N than starter fertilizer treatments at sidedress to compensate for the lack of N applied at planting in the control. Nitrogen concentration declined throughout the growing season at all sites.

At SEPAC19, after sidedressing (>458 GDD), N concentration was significantly higher in the control than in the starter treatments (Table 14). At 538 GDD, N concentration in the control treatment was 19.5 g N kg^{-1} while starter treatments averaged 17.5 g N kg^{-1}. At tasseling (854 GDD), the same response was observed, with the control increasing total N concentration by 2.6 g N kg^{-1} compared to the starter treatment average (17.1 vs 14.5 of g N kg^{-1}). This difference remained throughout the season until maturity. Final tissue N concentration was significantly higher in the control and NPK starter, ~9.0 g N kg^{-1}, than the N and NP treatments, ~ 8.3 g N kg^{-1}. Grain N concentration at SEPAC19 ranged from 12.9 to 13.4 g N kg^{-1} with no differences among treatments (Table 14).

At NEPAC19 after sidedressing (>322 GDD), N concentration was affected by the treatments in a similar manner to what occurred at SEPAC19 (Table 15). At 571 GDD, N concentration in the control treatment was 30.4 g N kg^{-1} while starter treatments averaged 28.2 g N kg^{-1}. The same effect was observed at tasseling (845 GDD) with a total N concentration of 17.3 and 15.3 g N kg^{-1} for the control and the starter treatments. At 649 and 728 GDD, N concentration with N-only starter was higher than NPK by 1.3 and 1.44 g N kg^{-1}, respectively; similar to what occurred at SEPAC19. In contrast to SEPAC19, no differences were detected in N stover concentration at maturity (1529 GDD) between control and starter treatments, with an average N concentration of 9.4 g N kg $^{-1}$. Grain N concentration ranged from 12.0 to 12.3 g N kg^{-1} with no treatment effects.

In 2020, nutrient concentration was measured only at NEPAC. Starter fertilizer affected nitrogen concentration at NEPAC20 at only 2 of 7 sampling dates (Table 16). Unlike NEPAC19, N concentration was below the sufficiency range at ~V4 (352 GDD). The NPK and NP treatments had 25 g N kg^{-1}, the N treatment had 23.5 g N kg^{-1}, and the control had the lowest N concentration, 22.2 g N kg^{-1}. Unlike NEPAC2019, N concentration did not differ between starter fertilizer and control treatments after N sidedressing (>248 GDD). At tasseling (825 GDD), N concentration averaged 16.7 g N kg^{-1}, with no significant differences among treatments. Similar to NEPAC 19, at maturity (1657 GDD), no differences were detected in N concentration with an average N concentration of 6.6 g N kg $^{-1}$. Grain N concentration averaged 11.8 g N kg^{-1} with no treatment effects (Table 16).

At TPAC19 before sidedressing, plant N concentration did not differ between control and starter fertilizer treatments (Table 17). After sidedressing (351 GDD), control plants had ~4 g N kg^{-1} more N than starter treatments across the vegetative stages (467-662 GDD). At tasseling (751 GDD), the N concentration of the control treatment was only 1.9 g N kg^{-1} higher than the starter treatment, and at maturity, the control was only 0.2 g N kg^{-1} more than the starter. The N concentration of the grain did not differ between treatments.

Phosphorus concentration at V4 was in the sufficiency range of 3-5 g P kg^{-1} at all sites in 2019 (Table 18-20). After V6, P concentration declined throughout the growing season. After sidedressing P concentration responded to starter fertilizer treatment in the same way as N concentration, P concentration was lower in starter fertilizer treatments than the control.

At SEPAC19 after 429 GDD, the control treatment had ~1 g P kg^{-1} higher P concentration than the starter treatments (Table 18). The difference between control and starter treatments was similar across the vegetative stages (V3-V13). At tasseling (854 GDD), P concentration ranged from 2.1 to 2.3 g P kg^{-1}, and there were no differences among treatments. At maturity, stover P concentration differences among treatments were no greater than 0.1 g P kg^{-1}. Similar to N, grain P concentration was unaffected by the treatments, averaging 2.6 g P kg^{-1}.

At NEPAC19, P concentration was affected at only 2 of 7 sampling dates (Table 19). Control plots had higher tissue P concentration (~0.2 g P kg^{-1}) than most starter treatments at ~V8 (571 GDD) and at tasseling (845 GDD); otherwise, there were no differences among treatments. At maturity (1529 GDD), there was no difference in stover (0.5 g P kg^{-1}) or grain (2.3 g P kg^{-1}) P concentration among treatments.

At NEPAC20, P concentration was below the sufficiency range (>3-5 g P kg^{-1}, Campbell, 2000) at all sampling dates, ranging from 1.9 to 2.7 g P kg^{-1} across all treatments (Table 20). The only treatment response was at ~V6 (446 GDD), where the control plot had a greater P concentration (2.7 g P kg^{-1}) than the NPK and N treatments (2.3 g P kg^{-1}), while NP did not differ from the control. At tasseling (825 GDD), there were no detectable differences among treatments (2.0 g P kg $^{-1}$). At maturity (1657 GDD), there was no difference in P concentration among the treatments; P stover concentration averaged 0.55 g P kg^{-1}. The addition of P in the NP and NPK starter treatments compared with the N starter did not affect P concentration at SEPAC19, NEPAC19, and NEPAC20.

At TPAC19, P concentration was affected only at 2 of 6 sampling dates, 467 and 589 GDD, and like the other sites, the control had a higher P concentration than the starter treatment (Table 21). At 467 GDD, P concentration was 4.8 and 3.3 g P kg^{-1} for the control and starter, while at 589

GDD, P concentration was 3.2 and 2.2 g P kg^{-1} for control and starter treatment. At tasseling (750 GDD), there were no detectable differences between treatments, P concentration was on average 1.6 g P $kg^{-1.}$ At maturity (1595 GDD), P concentration did not differ in stover and grain; stover P concentration averaged 0.5 g P kg^{-1} while grain P concentration averaged 2.3 g P kg^{-1}.

Potassium concentration at V4 was adequate (20-30 g K kg^{-1}, Campbell, 2000) at all sites, ranging from 20.2 to 44.3 g K kg^{-1} (Table 22-25). As with N and P, K concentration decreased with an increase in GDD at all sites and all treatments. At SEPAC19, K concentration was affected by treatments only at 2 of 7 sampling dates, 649 and 775 GDD (Table 22). At 649 GDD, K concentrations for the control, N, NPK, and NP treatments were 32.1>30.6=30.4>27.8 g K kg^{-1}, respectively. At 775 GDD, the control had the highest concentration with 24.5 g K kg^{-1} while starter treatments averaged 21.1 g K kg^{-1}. There were no differences among treatments in tissue K concentrations at tasseling (18.8 g K kg^{-1}) or in stover (16.7 g K kg^{-1}) or grain (3.55 g K kg^{-1}) at maturity.

At NEPAC19, similar results to SEPAC19 were observed, with only 2 of 7 sampling dates showing differences in K concentration (Table 23). At 454 GDD, the control had the highest K concentration, 38.9 g K kg^{-1}, while the starter treatments did not differ averaging 31.9 g K kg^{-1}. At 571 GDD, results showed a different pattern, NP starter had the lowest concentration, 29.5 g K kg^{-1}, compared to N (34.1 g K kg^{-1}), NPK (33.4 g K kg^{-1}), and control (35.0 g K kg^{-1}) which did not differ. There were no differences in K concentration among treatments at tasseling (17.4 g K kg^{-1}), or in stover (15.9 g K kg^{-1}) or grain (3.3 g K kg^{-1}) at maturity.

At NEPAC20, significant differences between treatments were recorded only at one sampling date when plants were at V6, 446 GDD (Table 24). At this time, the control treatment had the highest K concentration, 25.7 g K kg^{-1}, compared to the starter treatment's average 21.5 g K kg^{-1}, with no composition effect. There were no differences in K concentration among treatments at tasseling (21.9 g K kg^{-1}), or in stover (13.6 g K kg^{-1}) or grain (3.5 g K kg^{-1}) at maturity. The addition of K in the NPK starter treatments compared to the N and NP starter did not affect K concentration at SEPAC19, NEPAC19, or NEPAC20.

At TPAC19, control treatments had a higher K concentration than starter treatments but only at 2 of 6 sampled vegetative stages (Table 25). At 467 GDD, K concentration was 31.7 and 24.8 g K kg^{-1} for the control and starter treatment. At 589 GDD, K concentration was 22.7 and 18.3 g K kg^{-1} for the control and starter treatment. Differences were higher in magnitude compared to the other sites. There were no differences in K concentration among treatments at tasseling (15.3 g K kg^{-1}), or in stover (9.3 g K kg^{-1}) or grain (3.9 g K kg^{-1}) at maturity.

Sulfur concentration was adequate in plant tissue (>1.5-4.0 g S kg^{-1}, Campbell, 2000) at all sites at V4 in the 2019 and 2020 growing seasons (Tables 26-29). After V6, S tissue concentration decreased with time throughout the growing season. At SEPAC19, S concentration was significantly different between treatments at 4 of 7 sampling dates (Table 26). Similar behavior as N and P was observed with S concentration, where control had significantly higher S concentration than starter treatments, and there was no effect of starter fertilizer composition on S tissue concentration. The difference across the vegetative stages, 528-775 GDD, was ~1 g S kg^{-1}, with the control showing the highest S concentration. A similar response was observed at tasseling (854 GDD); S tissue concentration was 1.2 and 1.1 g S kg^{-1} for the control and the average of starter treatments. There were no differences in S concentration among treatments at maturity in stover (0.9 g S kg^{-1}) or grain (1.0 g S kg^{-1}).

At NEPAC19, 4 of 7 sampling dates showed significant differences among treatments for S concentration (Table 27). Similar to SEPAC19, control plots increased S concentration by 0.1 compared to starter treatments, 2.0 g S kg^{-1} vs 1.9 g S kg^{-1} (571 GDD) and 1.6 g S kg^{-1} vs 1.5 g S kg^{-1} (649 GDD). At tasseling (845 GDD), the same pattern was observed, where starter treatment had on average 0.1 g S ha^{-1} less S than the control (1.1 g S kg^{-1} vs 1.2 g S kg^{-1}). There were no differences in S concentration among treatments at maturity (1529 GDD), stover (0.9 g S kg^{-1}) or grain (1.0 g S kg^{-1}).

In contrast, at NEPAC20, there was no difference between control and starter treatments at any sampling date (Table 28); S concentration ranged from 1.1 to 1.9 g S kg^{-1} in vegetative stages, 1.0 to 1.1 g S kg^{-1} at tasseling, averaged 0.56 g S kg^{-1} in stover, and 0.9 g S kg^{-1} in grain at maturity.

In the case of TPAC19, differences were observed at 4 of 6 sampling dates, where starter treatments always had a lower S concentration (Table 29). At the earliest sampling date (467 GDD), starter S concentration was 1.5 g S kg^{-1} and control was to 1.9 g S kg^{-1}. The difference in magnitude increased with increased GDD in the vegetative stages (467 - 662 GDD), where starter treatments had, on average, 0.4 g S kg^{-1} less S than the control plots. There were no differences in S concentration among treatments at tasseling (0.9 g S kg^{-1}) or in grain (0.9 g S kg^{-1}). In contrast, stover S concentration at maturity was significantly higher in the control treatment, 0.5 g S kg^{-1}, than in the starter treatment, 0.4 g S kg^{-1}.

2.3.5 Nutrient content

Nutrient content was determined at SEPAC19, NEPAC19, TPAC19, and NEPAC20. Content of N, P, K, and S increased with increased GDD and plant development at all sites. At SEPAC19, N, P, K, and S contents were greater with starter than the control treatment at all vegetative stages (Tables 30-33). Starter fertilizer composition only occasionally affected nutrient content and differences that were detected at one sampling date did not persist at later sampling dates. Differences in nutrient content between the control and the mean of the three starter treatments increased with increased development.

At SEPAC19, the difference in N content between control and starter increased from ~0.4 to ~5 kg N ha^{-1} from 265 to 649 GDD (~V4 to ~V11) and then declined to ~3 kg N ha^{-1} at 775 GDD (~V15) (Table 30). Differences in P content between control and starter treatments were small at 265 GDD (V4) and at later growth stages differences ranged narrowly between 0.4 and 0.6 kg P ha^{-1} (Table 31). The difference in K content between control and starter increased from ~0.3 to ~12 kg K ha^{-1} from 265 to 649 GDD (~V4 to ~V11) and then declined to ~7 kg K ha^{-1} at 775 GDD (~V15) (Table 32). Sulfur content differences between the control and starter fertilizer treatments increased from ~0.03 to ~0.4 kg S ha^{-1} from 265 to 649 GDD (~V4 to ~V11) before declining to ~0.3 kg S ha^{-1} at 775 GDD (~V15) (Table 33).

At NEPAC19, differences in nutrient content between the control and starter fertilizer treatments were more infrequent than at SEPAC19. Nitrogen content increased with starter fertilizer at only the first two sampling dates (277-454 GDD). Starter, compared to the control, increased N content at 277 GDD (~V3) by 0.3 kg N ha^{-1} (Table 34). The difference increased at the second sampling date with plant N content for the starter treatments averaging 3.6 kg N ha^{-1} greater than that of the control. The starter treatments had increased P content compared to the control only at 454 GDD (~V5); 1.53, 1.44, 1.28, and 1.05 kg P ha^{-1}, for the NP, NPK, N, and control treatments, respectively. The two treatments containing P, NP and NPK, increased P content at this date compared to the control. With NP being significantly higher than N starter (Table 35). Potassium content was increased only at the first sampling date by the NPK starter treatment, compared to the control (Table 36). Plant K content with the NPK treatment was 1.5 kg

K ha^{-1} while plant K content with the NP, N, and control treatments did not differ, averaging 1.2 kg K ha^{-1}. Sulfur content was affected only at 454 GDD (~V7), plants with starter had 1.1 kg S ha^{-1} while control plants contained 0.75 kg S ha^{-1} (Table 37).

At NEPAC 20, nutrient content responses were similar to NEPAC19, with differences between control and starter not as frequent as at SEPAC2019. Nitrogen content was increased only at 352 GDD (~V4) by NP and NPK (10.5 and 8.4 kg N ha^{-1}), while the N-only starter and the control did not differ, averaging 6.8 kg N ha^{-1} (Table 38). Phosphorus content was affected at two sampling dates, 352 and 517 GDD (~V4, ~V7). At 352 GDD only NP starter increased P content compared to all the other treatments, 1.1 kg P ha^{-1} vs 0.8 kg P ha^{-1}(Table 39). At 517 GDD, the NPK, NP, and control had on average 3.2 kg P ha^{-1} while the N treatment had 2.5 kg P ha^{-1}. Potassium content was affected only at the first sampling date (~V4), with NP and NPK having the greater content, 9.6, 8.9, compared to the control and N only 8.1, and 7.3 kg K ha^{-1} (Table 40). Sulfur content responded similarly to P, at 352 GDD, the highest S content was recorded with the NP treatment, 0.7 kg S ha^{-1}, followed by NPK, 0.6 kg S ha^{-1}, and N and control, 0.5 kg S ha^{-1}, there were no differences in any other dates (Table 41).

At TPAC19, nutrient content was affected by the treatments only at two sampling dates during vegetative growth stages. Nitrogen content increased with starter fertilizer by 8 and 10 kg N ha^{-1} for 467 and 589 GDD, respectively (Table 42). Phosphorus content was increased at the same sampling date as N, starter had 2.4 and 3.5 kg P ha^{-1} versus 1.7 and 2.6 kg P ha^{-1} for the control (Table 43). Starter increased K content by 7 and 10 kg K ha^{-1} compared to the control for the same sampling dates (Table 44). Sulfur content was increased by 0.5 kg S ha^{-1} with starter fertilizer at 467 and 589 GDD (Table 45).

In summary, N content was greater with starter fertilizer treatments than the control and the difference between them increased through ~V6-V10, but declined thereafter. Phosphorus content was increased with increased plant development at all locations, with higher differences between ~V6 to ~V10. Similar to N, P content differences between starter and control declined after V10. Potassium content increased with increased plant development, but differences between the control and starter fertilizer treatments were less frequent than for N and P. Differences in K content between control and starter treatments peaked at ~V8-V10. Sulfur content increased with increased plant development at all locations with greater differences among control and starter treatments after ~V8. Starter composition effects were infrequent and inconsistent.

2.3.6 Onset of the reproductive stage, number of leaves per plant, and leaf position of the ear

Silk and tassel emergence in 2019 occurred earlier in starter treatments than in the controls. At SEPAC19 (854 GDD), only 40% of control plants had tasseled or silked while 90% of plants with starter fertilizer had tasseled or silked (Table 46). At NEPAC19 observations of tasseling/silking were not made until 97% of plants had tasseled or silked (845 GDD) with starter fertilizer (Table 46). At this time, only 87% of control plants had tasseled/silked. A narrow difference between control and starter treatments was observed at TPAC19, where starter treatments increase the appearance of silking and/or tasseling by only 10% (Table 47). It is important to keep in mind that the sampling to determine reproductive onset at TPAC19 was done early, limiting the ability to detect greater differences.

In the growing season of 2020, the timing of tasseling and/or silking was affected by starter fertilizer at all sites (Tables 46-47). Starter treatments increased the appearance of silking and/or tasseling by ~15% compared with control plots at SEPAC20 (93% starter vs 79% control), with no effect of starter composition. At NEPAC20, only the NPK starter was significantly different from the control, increasing the appearance of tassels and/or silks by 20%; the NP and N treatment were similar to the control, with a 55 and 42% of tassels and/or silks while the control had 41% of tassels and or silk appearance. In TPAC20, as in TPAC19, starter treatment significantly increased the appearance of silking and/or tasseling by 50% compared to the control treatment.

Starter treatments produced one more leaf than the control at SEPAC19 and NEPAC19. At SEPAC19, the starter had ~19 leaves while the control had ~18 leaves; At NEPAC19 starter had ~17 while the control had ~16. At SEPAC20, the magnitude difference was smaller than in 2019. The total number of leaves was 18.3, 18.2, and 17.8 for the NPK, NP and N, and the control treatments, respectively. At NEPAC20, there was no effect of starter treatments on final leaf number (Table 48).

At TPAC19, there were no differences among treatments for the total number of leaves, with the control having 15.9 and the starter having 16.7 (Table 49). At TPAC20, plants with starter averaged ~2.5 more leaves than the control, 17.8 and 15.3 leaves, respectively (Table 49).

The position of the ear on the plant averaged one leaf higher with starter fertilizer than the control at SEPAC19 and NEPAC19 and 0.3 leaves higher at SEPAC20 (Table 50). The subtending ear leaf number was unaffected at NEPAC20 (Table 50). In the case of TPAC, differences occurred in 2020 and in 2019, with plants without starter positioning the ear 0.2 and 0.3 leaves higher than with starter, respectively (12.3 vs 12.1 and 12.1 vs 11.8) (Table 51). Leaf number and ear position did not differ among the three starter fertilizer composition at most of the sites.

2.3.7 Grain yield and yield components

Grain yield increased with starter fertilizer, compared to the control treatment, at SEPAC and TPAC, but not at NEPAC in 2019. At SEPAC19, starter fertilizer increased yield ~800 kg ha^{-1} versus the control with no differences among starter fertilizer composition (Table 52). At TPAC19, the NP starter increased yield ~1,000 kg ha^{-1} compared to the control (Table 53). Based on a relatively small sample size, there were no starter fertilizer treatment effects on the number of rows per ear, number of kernels per row, and weight of 1000 kernels at any of the sites in 2019 (Table 54-56), despite the yield increases measured at field scale level using combines and yield monitors.

Grain moisture was generally drier with starter fertilizer than without, but starter fertilizer composition did not affect grain moisture (Table 52 and 53). Grain moisture content was 7.0, 1.2, 5.7, and 5.3% lower at SEPAC19, SEPAC20, TPAC19, and TPAC20 with starter versus no starter, respectively. Starter fertilizer did not affect grain moisture content at NEPAC19 or NEPAC20.

Grain yield increased with starter fertilizer, compared to the control treatment, at SEPAC20, but not at NEPAC20 or TPAC20 (Tables 52-53). At SEPAC20, the average yield increase due to starter fertilizer was 500 kg ha^{-1} compared to the control, but there were no differences due to starter fertilizer composition. At SEPAC20, number of kernel rows per ear was the only yield component affected by starter fertilizer (an increase of 0.7 rows per ear), but there were no differences among the starter fertilizers differing in composition (Table 57). At NEPAC20, starter fertilizer only affected kernel number per row (Table 58) and, interestingly, the effect was negative (39 for the control and 37 on average for the starter treatments). At TPAC20 conversely, starter fertilizer increased kernel number per row (42 versus 40 for the control). Again, as in 2019, the small sample size did not reflect the yield measurements made with the combine.

2.4 Discussion

2.4.1 Effect of starter fertilizer on leaf appearance and dry matter accumulation

Starter fertilizer increased leaf appearance at all sites in 2019 and 2020. The difference between the starter treatments and the control treatment in number of collared leaves increased during the vegetative growth period from 0.2 to 1.6 more leaves between V4 and V15 across all sites and years, regardless of the composition of the starter fertilizer. Lee (2020) found similar effects of starter fertilizer on leaf appearance rate at TPAC in 2016 and SEPAC and NEPAC in 2018, although he did not compare differences in starter fertilizer composition. In his study, starter fertilizer increased the number of visible leaf collars per plant after 200 GDD; the difference between control and starter treatments increased with increased GDD, increasing the number of leaf collars by one entire leaf at NEPAC and SEPAC at >600 GDD. In another study in NEPAC and SEPAC fields in 2015 and 2016, Hornaday (2017) also reported accelerated leaf appearance with starter fertilizer (rates and placement of NP starter fertilizers) compared to the control. In his study, Hornaday (2017), similar to Lee (2020) reported more leaves in the starter treatments compared to the control from V4 through V12 (150-700 GDD) and increased differences among treatments with increased GDD. At SEPAC at 671 GDD, starter fertilizer increased total collared leaves by more than 2 compared to the control, 11.2 vs 13.5. These results are similar to Lee (2020) who reported a higher percentage of plants with 19 leaves in the starter treatments compared to control. A study evaluating starter fertilizer and four different hybrids in Iowa reported that the production of more leaves was more frequent when starter (20-20-20) was applied; an increase of one leaf with starter fertilizer was recorded in the two years of the experiment (Eik, 1962).

The difference in leaf appearance in this study and the increase in above-ground dry matter was more consistent at SEPAC and TPAC than at NEPAC. Differences between starter and control treatments were higher in magnitude at vegetative stages ranging from 20 to 50% more dry matter with starter fertilizer. In reproductive stages, the increase in dry matter was not as consistent as in vegetative stages. Lee (2020) found similar results, reporting an increase in shoot dry matter with starter fertilizer. The results indicated that starter treatment accumulated >80% more dry matter than the control at TPAC after 250 GDD. These results agree with Bullock et al. (1993) in Illinois, who measured leaf area index and above-ground dry matter, finding starter fertilizer increased plant growth rate compared to no starter fertilizer as early as 400 GDD after planting, but differences did not remain at harvest. In a study conducted in Pennsylvania, Roth et al. (2006) found an increase in early growth with starter fertilizer compared to no starter fertilizer based on a greater dry matter accumulation from plants sampled around V6-V7. Kaiser et al. (2005) observed similar results in trials evaluating starter fertilizers where at six of eight sites the use of starter fertilizer significantly increased dry matter accumulation. The increase in above-ground matter accumulation was related to more robust plants, taller plants, and more leaves (Till et al., 2018; Kaiser et al., 2005). Increased dry matter with starter fertilizer has been a typical result across different locations when starter fertilizer was applied (Buah et al., 1999; Lauzon & Miller, 1997; Rehm & Lamb, 2009).

In my study, the difference in the number of leaves and dry matter in the vegetative stages suggest that plants grow faster with starter fertilizer than without. However, dry matter with starter fertilizer and control treatments was similar when compared at the same number of collared leaves. This result agrees with Lee (2020), who found that dry matter did not differ between starter treatments and control when normalized for the same number of leaf collars. These studies indicated that plants have an accelerated leaf appearance, but reach their maximum crop growth rate and stop accumulating dry matter at the end, having similar total dry matter at maturity with or without starter.

Where starter fertilizers differing in composition were compared at NEPAC and SEPAC, there were few differences in the response of collared leaf appearance and above-ground dry matter to starter fertilizer (N vs NP vs NPK). Thus, adding P and K to the N starter had no greater benefit than N alone at our sites. These results were similar to those of Woodard et al. (2002), where the addition of P and K did not increase plant growth compared to N-only starter. Additionally, Gordon and Pierzynski (2006) found that the addition of K did not enhance dry matter when using NP starter fertilizers in a Kansas study. Mallarino et al. (2011) evaluated the addition of NPK and NK starter. The authors reported an increased in dry matter accumulation with the NPK starter but not with the NK starter at four of six sites. These results were obtained at soil test K levels ranging from low to optimum (<90-170 mg kg^{-1}), and P levels ranging from very low to very high (9->31 mg kg^{-1}). Tekulu et al. (2020) evaluated twelve different mixes of starter fertilizer containing N (0, 15 and 30 kg ha^{-1}) and P (0, 23, 46, and 69 kg ha^{-1}). The combination of 30 kg N ha^{-1} and 69 kg P ha^{-1} produced the greatest increase in plant height (+11.1 cm) compared to the control. In addition, the authors reported increased plant height as a response to the two lowest rates of N and

P. In a study evaluating N, P, K, S, and Zn starter fertilizers, Gordon & Pierzynski (2006) determined 34 kg N and 15 kg P ha^{-1} as the best combination to enhance early growth of different corn hybrids.

2.4.2 Nutrient concentration and content

Whole plant N concentration increased with starter fertilizer, compared to the control, at early growth stages (<V6) at all site-years. After the first sampling dates, N concentration decreased with increased dry matter accumulation and plant development and the control treatment had equivalent or higher N concentration than the starter fertilizer treatments. An increase in N concentration (8.8 g kg^{-1}) with starter fertilizer compared to no starter at early growth stages was also reported by Hornaday (2017). Another study also reported an increased N concentration of 0.4 g kg^{-1} in plants around V6 when starter fertilizer was used (Roth et al., 2003). The authors concluded that the response to starter fertilizer was related to earlier access to N. Increased N concentration of 0.2 to 1.0 g kg^{-1} with NP or NPK starter compared to control treatments was also reported by Touchton & Karim (1986).

After sidedressing, plants in the control treatment had equal or greater N concentration than plants in starter fertilizer treatments. At SEPAC19, N concentration was higher in control by 2 g N kg^{-1} than in the starter treatments. Similar results were observed at NEPAC19 and TPAC19, but in NEPAC20 N concentration was unaffected after sidedressing.

Phosphorus concentration did not differ between starter and control treatments prior to sidedressing. Phosphorus concentration decreased over time, and when differences in P concentration were detected, the control usually had a higher P concentration than the starter treatments, despite P being applied in two of the starter treatments. Among starter fertilizer treatments, in general, there was no difference in P concentration. Our results are similar to those found by (Hornaday, 2017) who reported a decrease in P concentration with starter fertilizer application at all the 3 sites in 2015. Vetsch and Kaiser (2016) reported increased dry matter with starter fertilizer, but no differences in P concentration of plants sample at V5 with P-only starter fertilizers (22 and 33 kg P ha^{-1}) compared to no starter fertilizer and lower rates of P. The authors argued the lack of response in P concentration as an effect of increased plant dry matter and dilution of the P by greater growth.

Potassium concentration decreased with increased GDD. When differences were detected among treatments, the control had higher K concentration than the starter treatments. These results were similar to Hornaday (2017), who reported a decrease in of 4.4 to 7.4 g K kg^{-1} with starter fertilizer compared to the control, when evaluating starter fertilizer in Indiana fields. Mallarino et al. (2010) in contrast, reported an increase in early K concentration at 3 of 8 sites (~0.4 g kg^{-1}) when evaluating K starter fertilizer across Iowa. In this study, plots were fertilized with 60 kg K ha^{-1} at planting and plant samples were obtained at V5-V6;

Sulfur concentration increased slightly (1 g S kg^{-1}) at early planting dates with starter fertilizer (before sidedressing), but decreased with increased GDD similar to what occurred with N, P, and K concentration. After early sampling dates, when differences among treatments were recorded, the starter treatments, compared to the control, decreased S concentration an average of ~1 g kg^{-1}. Hornaday (2017) reported decreased S concentration of 0.4 g kg^{-1} by the starter treatments, compared to the control. The decrease in nutrient concentration across vegetative stages has been related to faster crop development, enhancing plant dry matter and dilution of nutrients in plant tissue (Vetsch and Kaiser, 2016).

Grain nutrient concentration (N, P, K, and S) was unaffected by the starter fertilizer treatments, including the control, at any site year. These results were similar to those found by Hornaday (2017), who found no effects of starter fertilizer in P, K, and S grain concentration. However, he reported an increase of N concentration (1.2 g kg^{-1}) when starter fertilizer was used.

Plant N, P, K, and S content increased with increased GDD. Differences in nutrient content occurred between starter treatments and the control 70% of the time, but rarely were there differences among starter fertilizer treatments differing in composition. Differences in N content in vegetative stages increased with starter fertilizer taking up 0.4 to 4.9 kg N ha^{-1} more N than the control in vegetative stages across all sites (V4 to V14). This result agrees with Lee (2020) who found an exponential increase in nutrient content with plant development. Kaiser and Rubin (2013), also found an increase in nutrient content for N, P, K, and S when using starter fertilizer across three different soils. Our results indicate that the increase in nutrient content was associated with increased plant dry matter since dry matter increased whereas nutrient concentration decreased. Roth et al. (2006) also reported increases in nutrient uptake as a response to starter fertilizer that was similar to the magnitude of the increases in early growth.

2.4.3 Onset of the reproductive stage, number of leaves per plant, and leaf position of the ear

Plants with starter fertilizer silked and/or tasseled earlier than control plants at all sites in 2019 and 2020. Earlier silking/tasseling was likely related to the plants' accelerated leaf appearance with starter fertilizer compared to the control. An earlier onset of reproductive growth stages has been noted in some starter fertilizer studies. Lee (2020) found that starter fertilizer resulted in earlier silking and/or tasseling as a response to starter fertilizer at the same sites used in this study. These results also agree with other field studies. For example, starter fertilizer reduced the number of GDD to reach silking (766 to 686 GDD) for 3 of 5 hybrids (Gordon et al., 1997). Also, in a summary of 15 site-years Mascagni and Boquet (1996) found that starter fertilizer consistently decreased the time needed to reach silking by 3 to 4 days in all site-years. Perhaps the late planting date at NEPAC19, one month later than NEPAC20, explains the lack of starter fertilizer effect on silking at this site-year. Cromley et al. (2006) found that earlier planting dates resulted in a larger difference in calendar time needed to reach reproductive growth stages between starter fertilizer and no starter fertilizer treatments.

The final number of leaves per plant increased at 3 of 6 site-years with starter treatments having 0.4 to 1.0 more leaves per plant than the control, regardless of starter composition. Starter fertilizer, compared to the control, increased the number of plants with 18 or 19 final leaves rather than 17 to 18 that were more frequent in the control treatment. The position of the ear averaged 0.2 to 0.9 leaves higher on the plant with starter fertilizer at three sites. This result agrees with Lee (2020) who found that starter fertilizer reduced the frequency of plants with 17 final leaves and increased the frequency of plants with 18 and 19 leaves at the same sites used in this study. Similarly, Hornaday (2017) at 3 of 4 sites in Indiana found that starter fertilizer, compared to the control, increased the final number of leaves 0.2 to 0.6 leaves plant^{-1} and the position of the ear was 0.2 leaves higher.

2.4.4 Grain yield and yield components

Grain yield was increased by starter fertilizer at three sites in 2019 and one site in 2020, but starter fertilizer composition did not affect grain yield at any site-year. In 2019 at SEPAC and NEPAC, grain yields with starter fertilizer, compared to the control, were ~800 and ~330 kg ha^{-1} greater, respectively. At TPAC19, the starter treatment increased yield 1134 kg ha^{-1} compared to the control. In 2020, grain yield was increased with starter fertilizer, compared to no starter, only at SEPAC, where starter fertilizer increased yield ~400 kg ha^{-1}. These results were similar to those found by Hornaday (2017), who reported yield increases in 3 site-years at SEPAC and NEPAC ranging from 357 to 928 kg ha^{-1}. In contrast, at the same sites in 2016 and 2018 there were no increases in grain yield with the use of starter fertilizer compared to the control (Lee, 2020). Yield increases to starter fertilizer were less frequent than effects on leaf appearance, dry matter, or days to reach reproductive growth stages in this study, which is similar to the findings of Lee (2020) and Hornaday (2017). Our results were also similar to those found by Vetsch and Randall (2000), who recorded an increase of 500 kg ha^{-1} in grain yield when starter fertilizer was applied at two of the three study years. In Wisconsin, one study evaluating starter fertilizer reported a yield increase of 300 kg ha^{-1} on average, compared to control treatments on a 3-year study indicating that yield responses can be site-specific and dependent on soil P and K levels (Bundy & Andraski, 1999). Additionally, Bermudez and Mallarino (2002) found a low yield response to starter fertilizer (2 of 11 sites) even when the response in early growth was most consistent. An increase in early growth rate and early dry matter accumulation were not good indicators of increased grain yield (Bullock et al., 1993; Roth et al., 2006). The more frequent responses in this study can be attributed to the higher availability of nutrients, primarily N, for root and plant development close to the seed.

Grain moisture was reduced by starter fertilizer by at least 5 g kg^{-1} at five of six site-years in comparison to the control. This result was likely, in part, related to the faster leaf appearance and earlier silking and/or tasseling induced by starter fertilizer which would allow the grain to reach maturity faster and thus lower moisture at the time of harvest. However, the potential contribution of starter fertilizer treatments altering grain fill rate, grain maturation, and subsequent drying was not examined. Starter fertilizer decreased grain moisture by 11 g kg^{-1} at 9 of 10 locations in Indiana (Hornaday, 2017). Results of studies in 2016 and 2018 evaluating starter fertilizer at the same sites of the present study, showed decreased moisture at 4 of 5 sites years; with starter decreasing moisture by ~3 g kg^{-1} compared to control (Lee, 2020). Starter fertilizer, compared to a control, reduced grain moisture at three of four locations regardless of yield response (Roth et al., 2003). Bundy and Andraski (1999) found a decrease of 2 g kg^{-1} moisture with starter fertilizer across several studies. In addition, Kaiser et al. (2016) found a decrease in grain moisture using a low rate of pop-up starter fertilizer of at least 2 g kg^{-1} (150-152 g kg^{-1}). Different research studies cited here recorded similar results to the ones obtained in this study, indicating that reduced grain moisture is a common response to starter fertilizer and could potentially help reduce cost in grain drying after harvest.

The yield components of rows ear^{-1}, grain ear^{-1}, weight kernel^{-1} were mostly unaffected by starter fertilizer. This result agrees with Pierson (2013), who found that these variables differed among hybrids but were unaffected by starter fertilizer.

2.5 Conclusions

The objectives of this study were to evaluate the effects of starter fertilizer on crop growth and development as well as yield components in a continuous corn no-till cropping system. In addition, we wanted to see if adding P and K to the starter fertilizer had additional benefits to plant growth. In the studies of starter composition carried out at NEPAC and SEPAC, the results indicated that for these specific sites, the addition of P and K to the N-only starter fertilizer did not affect corn growth rate, plant dry matter, and variables associated with yield responses.

Starter fertilizer of any composition increased the appearance of total collared leaves at all locations. The magnitude of the difference between the starter and the control plots increased with increased GDD, and at the last sampling date ranged from 0.2 to 1.6 more leaves with starter than without across the sites. The total number of leaves was increased by one more leaf at three of six site-years when starter fertilizer was applied.

Starter fertilizer increased above-ground dry matter throughout the growing season at four of six sites, with NEPAC having inconsistent results. The increase in dry matter was observed at a higher frequency across early growth stages, peaking around ~V16 to R1. At TPAC, starter fertilizer doubled dry matter prior to R1.

The increase in plant dry matter and appearance of collared leaves was related to faster crop development in early stages. This faster crop development resulted in plants reaching silking and/or tasseling in a shorter amount of time at all site-years. Starter fertilizer affected ear leaf position, with the ear positioned slightly higher on the plant than in plants without starter fertilizer. The average starter effect on subtending ear leaf number was +0.2, +0.8, +0.3, 0.0, +0.2, and -0.3 at SEPAC19, NEPAC19, SEPAC20, NEPAC20, TPAC19, AND TPAC20, respectively.

Starter fertilizer inconsistently affected whole plant nutrient concentrations. Nutrient concentration decreased as growth stage progressed, indicating a possible dilution effect related to larger plants. Additionally, nutrient concentrations in control plants were greater compared to those with starter fertilizer after sidedressing was applied at all the sites-year. Whole plant nutrient content increased over time when starter fertilizer was applied. Nutrient content followed a similar trend as dry matter accumulation, indicating a possible relationship between these two variables. Grain nutrient concentration was unaffected by starter fertilizer at all sites in this study.

Earlier silking and tasseling associated with starter fertilizer is likely the cause of lower grain moisture at harvest. Starter fertilizer, compared to the control, decreased grain moisture at four of six sites by at least 5 g kg^{-1}. Yields increases were more consistent at TPAC and SEPAC than at NEPAC. Starter fertilizer increased yield from 300 to 1000 kg ha^{-1} compared to the control. Despite measuring corn yield increases at a field scale level with the combine, smaller ear sample sizes could not detect any starter fertilizer treatment effects on the number of rows per ear, number of kernels per row, and weight of 1000 kernels that explained the starter fertilizer effects on yield.

2.6 Challenges and future work

Studying the effects of starter fertilizer is a challenge since the real effect in early crop growth is not completely understood. The usual responses to starter fertilizer are a faster leaf development and an apparent dry matter accumulation increase noticed at the same point in time. However, when comparing at the same plant development point increases in dry matter and leaf appearance are not always detected. To try to better understand the effect of starter fertilizer on early crop plant development requires more frequent sampling. To process a larger number of samples requires more labor which results in more expensive experiments. Additionally, since a yield increase is not a frequent response to starter fertilizer, more research is needed to understand the relationship between early crop development variables and yield increases.

In addition, it is important to analyze the economic impact of starter fertilizer in corn production. Lower grain moisture at harvest is a usual response to starter fertilizer, so it is necessary to know what the economic benefit is associated with this response even with no yield increase. Future research should study the response to starter fertilizer under different cropping systems practices like crop rotations, conventional tillage, and cover crops.

Table 1. Soil series information for field experiments conducted at the Southeast (SEPAC), Northeast (NEPAC), and Throckmorton (TPAC) Purdue Agricultural Centers.

Location	**Series**	**Texture**	**% of field**	**Classification**
SEPAC 39.044282, -85.524304	Avonburg	Silt loam	40%	fine-silty, mixed, active, mesic Aeric Fragic Glossaqualfs
	Nabb	Silt loam	24%	fine-silty, mixed, active, mesic Aquic Fragiudalfs
	Ryker- Muscatatuck	Silt loam	16%	fine-silty, mixed, active, mesic Typic Paleudalfs
	Cobbsfork	Silt loam	12%	fine-silty, mixed, active, mesic Fragiaquic Paleudults
NEPAC 40.241873, -85.147649	Haskin		40%	
	Rawson	Loam Sandy loam	28%	fine-loamy, mixed, active, mesic Aeric Epiaqualfs fine-loamy, mixed, active, mesic Oxyaquic Hapludalfs
	Glynnwood		18%	
TPAC 40.270248, -86.884779	Toronto- Millbrook	Silt loam	40%	fine-silty, mixed, superactive, mesic Udollic Epiaqualfs
	Lauramie	Silt loam	26%	fine-silty, mixed, superactive, mesic Udollic Endoaqualfs
	Drummer	Silt loam	28%	fine-loamy, mixed, active, mesic Mollic Hapludalfs

Table 2. Mean and standard deviation for soil pH, cation exchange capacity (CEC), organic matter (OM), and Mehlich 3-extractable nutrients from starter fertilizer experiments conducted at the Southeast (SEPAC), Northeast (NEPAC), and Throckmorton (TPAC) Purdue Agricultural Centers in 2019 and 2020. Data obtained from soil samples collected at pre-planting.

Location and year	pH	CEC	OM	P	K	Mg	Ca	Na	S	Zn	Mn	Fe	Cu	B
		$cmol_c$ kg^{-1}	g kg^{-1}	---------- mg kg^{-1} ----------										
SEPAC 2019	6.3 ±0.4	8.1 ±1.4	21 ±2	24 ±6	96 ±21	151 ±28	1100 ±240	10 ±1	9.0 ± 2.0	1.1 ±0.4	143 ±35	120 ±37	0.9 ±0.2	0.4 ±0.1
NEPAC 2019	6.3 ±0.6	9.8 ±3.7	21 ±7	41 ±15	133 ± 19	208 ±80	1270 ±603	11 ±2	9.0 ± 2.0	1.2 ±0.4	73 ±22	138 ±21	1.4 ±0.6	0.3 ±0.1
TPAC 2019	6.6 ±0.3	13.2 ±1.0	22 ±3	38 ±10	130 ± 19	288 ±28	1852 ±220	14 ±1	7.0 ± 1.0	3.7 ±1.2	121 ±41	145 ±24	2.0 ±0.4	0.3 ±0.1
SEPAC 2020	6.2 ±0.3	7.9 ±0.6	22 ±2	21 ±4	123 ± 19	133 ±27	1018 ±93	8 ±1	7.2 ± 1.3	0.8 ±0.1	127 ±18	97 ±11	0.5 ±0.1	0.3 ±0.1
NEPAC 2020	6.5 ±0.4	8.2 ±1.7	17 ±4	26 ±2	102 ± 12	198 ±54	1122 ±245	9 ±1	8.5 ± 2.1	0.9 ±0.3	47 ±16	133 ±9	0.9 ±0.3	0.1 ±0.1
TPAC 2020	6.6 ±0.4	11.4 ±0.8	26 ±2	34 ±12	117 ± 26	263 ±24	1667 ±189	6 ±1	7.0 ± 1.6	3.2 ±1.3	88 ±22	133 ±12	1.9 ±0.5	0.3 ±0.1

Table 3. Growing degree days (GDD) calculated using temperatures in Celsius degrees for each sampling date. Temperature data obtained from Indiana state climate office, https://ag.purdue.edu/indiana-state-climate/

2019			2020		
Site	Date	GDD	Site	Date	GDD
SEPAC19	27-Jun	265	SEPAC20	24-Jun	288
	8-Jul	429		2-Jul	401
	15-Jul	528		9-Jul	505
	23-Jul	649		17-Jul	611
	2-Aug	775		28-Jul	776
	8-Aug	854		5-Aug	871
	7-Oct	1602		28-Oct	1632
NEPAC19	28-Jun	277	NEPAC20	18-Jun	352
	10-Jul	454		26-Jun	446
	18-Jul	571		1-Jul	517
	24-Jul	649		8-Jul	619
	30-Jul	729		16-Jul	726
	9-Aug	845		23-Jul	825
	24-Oct	1529		12-Oct	1657
TPAC19	3-Jul	351	TPAC20	19-Jun	307
	11-Jul	467		25-Jun	383
	19-Jul	589		30-Jun	456
	25-Jul	662		10-Jul	609
	1-Aug	750		18-Jul	717
	1-Nov	1595		29-Jul	876
				24-Oct	1689

Table 4. Effect of starter fertilizer differing in composition on the number of visible leaf collars at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C				
	265	429	528	649	775
Treatment†	Number of visible leaf collars				
control	3.94 c‡	6.18	7.8 b	10.4 b	13.4 b
N	3.97 b	6.32	8.3 a	11.3 a	15.0 a
NP	4.01 a	6.36	8.4 a	11.3 a	15.0 a
NPK	3.98 b	6.33	8.4 a	11.3 a	14.9 a
P value	0.001	ns	<0.001	<0.001	<0.001
CV	1	5	3	5	5
R^2	0.24	0.08	0.6	0.57	0.7
Control vs starters	0.03	ns	<0.01	0.02	<0.01

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 5. Effect of starter fertilizer differing in composition on the number of visible leaf collars at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C				
	277	454	571	649	728
Treatment†	Number of visible leaf collars				
control	3.3 b‡	6.4 c	8.1 b	10.2 b	12.3 c
N	3.3 b	6.7 b	8.4 a	10.7 a	13.1 b
NP	3.5 a	6.9 a	8.5 a	10.8 a	13.3 a
NPK	3.5 a	6.9 a	8.5 a	10.7 a	13.2 ab
P value	0.008	<0.001	<0.001	<0.001	<0.001
CV	4	4	4	4	4
R^2	0.44	0.71	0.82	0.81	0.78
Control vs starters	0.01	<0.001	<0.001	<0.001	<0.001

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 6. Effect of starter fertilizer differing in composition on the number of visible leaf collars at SEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C				
	288	401	505	611	776
Treatment†	Number of visible leaf collars				
control	3.4	5.8 b‡	7.4 c	9.3 b	13.8 b
N	4.2	6.0 a	7.8 ab	9.7 a	14.6 a
NP	4.2	6.0 a	7.7 b	9.7 a	14.5 a
NPK	3.9	6.0 a	7.8 a	9.7 a	14.6 a
P value	ns	<0.01	<0.001	<0.001	<0.001
CV	18	2	3	2	3
R^2	0.25	0.67	0.80	0.70	0.83
Control vs starters	0.03	<0.001	<0.001	<0.001	<0.001

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 7. Effect of starter fertilizer differing in composition on the number of visible leaf collars at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C				
	352	446	517	619	726
Treatment†	Number of visible leaf collars				
control	4.01 b‡	5.6	7.1 b	9.0 b	12.5
N	4.01 b	5.6	7.1 b	9.0 b	12.3
NP	4.07 a	5.6	7.1 b	9.0 b	12.2
NPK	4.09 a	5.9	7.3 a	9.2 a	12.5
P value	0.05	ns	<0.05	0.07	ns
CV	2	10	2	3	4
R^2	0.51	0.66	0.69	0.57	0.55
Control vs starters	0.09	0.43	0.07	0.46	0.38

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 8. Effect of NP starter fertilizer on the number of visible leaf collars at TPAC19.

	Growing Degree Days (GDD) °C			
	351	467	589	662
Treatment†	Number of visible leaf collars			
control	4.1 b‡	6.2 b	8.4 b	10.0 b
starter	4.9 a	6.8 a	9.2 a	11.3 a
P value	<0.001	<0.01	<0.01	<0.01
CV	10	6	5	7
R^2	0.98	0.89	0.88	0.9

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 9**.** Effect of NP starter fertilizer on the number of visible leaf collars at TPAC20.

	Growing Degree Days (GDD) °C				
	307	383	456	609	717
Treatment†	Number of visible leaf collars				
control	3.3 b‡	4.4 b	5.9 b	8.5 b	10.8 b
starter	3.9 a	5.0 a	6.5 a	9.5 a	12.1 a
P value	<0.001	<0.001	<0.001	<0.001	<0.001
CV	9	7	5	6	6
R^2	0.95	0.87	0.94	0.90	0.98

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 10**.** Effect of starter fertilizer differing in composition on above-ground plant dry matter at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C						
	265	429	528	649	775	854*	1602+
Treatment†	Dry Matter, kg ha^{-1}						
control	25 b‡	190 c	441 b	1002 b	2073 b	2804 c	12174 b
N	33 a	274 b	693 a	1502 a	2709 a	3186 b	13070 a
NP	33 a	312 a	767 a	1497 a	2858 a	3454 a	13001 a
NPK	31 a	306 ab	726 a	1479 a	2719 a	3427 a	12156 b
P value	0.05	<0.001	<0.001	<0.001	<0.001	<0.001	<0.1
CV	27	25	28	21	14	13	10
R^2	0.20	0.47	0.62	0.58	0.65	0.39	0.23
Control vs starters	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	0.14

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 11. Effect of starter fertilizer differing in composition on plant dry matter at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means

	Growing Degree Days (GDD) °C						
	277	454	571	649	728	845*	1529+
Treatment†	Dry Matter, kg ha^{-1}						
control	27	288 b‡	964 b	1716	2676	4128 b	13880
N	28	379 a	1148 a	1918	2921	4621 b	14087
NP	30	423 a	1217 a	1818	2844	4824 a	13676
NPK	34	417 a	1195 a	1755	2893	4828 a	14117
P value	ns	<0.01	0.02	ns	ns	0.07	ns
CV	20	23	17	14	9	12	7
R^2	0.07	0.46	0.45	0.34	0.14	0.14	0.07
Control vs starters	0.11	<0.001	0.003	0.21	0.05	0.01	0.84

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 12**.** Effect of starter fertilizer differing in composition on plant dry matter at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C						
	352	446	517	619	726	825*	1657[+]
Treatment†	Dry Matter, kg ha^{-1}						
control	313 bc‡	570	1155	2270	4983	6585	18873
N	283 c	584	1092	2131	4968	6358	18027
NP	412 a	571	1176	2170	4698	7015	17544
NPK	345 b	596	1281	2386	5252	6943	17573
P value	<0.001	ns	ns	ns	ns	ns	ns
CV	20	21	19	15	20	14	13
R^2	0.54	0.19	0.24	0.03	0.61	0.40	0.58
Control vs starters	0.10	0.36	0.74	0.78	0.97	0.66	0.12

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).
*Tasseling and/or silking.

[+]Physiological maturity.

Table 13. Effect of NP starter fertilizer on above-ground plant dry matter at TPAC19.

	Growing Degree Days (GDD) °C					
	351	467	589	662	750/850*	1595^{+}
Treatment†	Dry Matter, kg ha^{-1}					
control	104 b‡	362 b	838 b	1419 b	3936 a	14514
starter	207 a	749 a	1555 a	2112 a	3033 b	14511
P value	0.04	<0.001	<0.001	0.003	<0.01	ns
CV	55	45	35	30	17	8
R^2	0.37	0.91	0.88	0.76	0.59	0.27

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking sampling dates for starter and control treatments, samples taken in two different dates. Earlier date for control and later for starter.

$^{+}$Physiological maturity.

Table 14. Effect of starter fertilizer differing in composition on the nitrogen concentration (g N kg^{-1} tissue) at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	265	429	528	649	775	854*	1602+	grain
Treatment†	nitrogen concentration, g kg^{-1} tissue							
control	30.6 b‡	23.7	19.5 a	21.9 a	18.1 a	17.1 a	9.1 a	13.1
N	37.6 a	24.7	17.4 b	18.2 b	15.5 b	15.1 b	8.2 b	12.9
NP	39.2 a	24.2	17.5 b	18.3 b	14.1 c	13.8 c	8.3 b	13.3
NPK	38.6 a	24.6	17.6 b	17.6 b	14.5 bc	14.6 bc	8.9 a	13.4
P value	<0.001	ns	<0.1	<0.001	<0.001	<0.001	0.01	ns
CV	11	10	12	12	14	13	9	5
R^2	0.71	0.16	0.26	0.55	0.49	0.36	0.17	0.03
Control vs starters	<0.001	0.58	0.06	<0.001	0.009	0.05	0.01	0.13

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 15. Effect of starter fertilizer differing in composition on the nitrogen concentration (g N kg^{-1} tissue) at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	277	454	571	649	728	845*	1529^{+}	Grain
Treatment†	nitrogen concentration, g kg^{-1} tissue							
control	32.3 b‡	32.8	30.4 a	24.4 a	20.3 a	17.3 a	9.6	12.1
N	41.6 a	32.9	28.6 b	23.6 ab	19.9 a	15.7 b	9.5	12.3
NP	38.2 a	33.6	27.6 b	22.9 bc	19.4 a	15.1 b	9.3	12.0
NPK	38.1 a	31.3	28.3 b	22.3 c	18.5 b	15.1 b	9.1	12.1
P value	<0.05	ns	<0.01	<0.05	<0.01	<0.01	ns	ns
CV	14	12	8	8	7	10	6	3
R^2	0.34	0.46	0.74	0.54	0.62	0.55	0.11	0.05
Control vs starters	<0.01	0.84	<0.001	<0.01	<0.1	<0.001	0.19	0.78

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

$^{+}$Physiological maturity.

Table 16. Effect of starter fertilizer differing in composition on the nitrogen concentration (g N kg^{-1} tissue) at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	352	446	517	619	726	825*	1657⁺	grain
Treatment†	nitrogen concentration, g kg^{-1} tissue							
control	22.2 b‡	26.5	25.7	23.1	20.1 a	17.1	6.9	11.6
N	23.5 ab	25.3	27.2	25.1	18.6 ab	17.1	6.7	11.6
NP	25.6 a	24.6	26.4	21.1	19.2 a	16.3	5.9	11.9
NPK	24.6 a	24.2	25.6	20.9	17.1 b	17.1	6.8	12.1
P value	0.08	ns	ns	ns	0.06	ns	ns	ns
CV	13	17	10	18	12	8	11	6
R^2	0.42	0.54	0.15	0.16	0.24	0.13	0.01	0.27
Control vs starters	0.03	ns	ns	ns	0.06	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

⁺Physiological maturity.

Table 17. Effect of NP starter fertilizer on the nitrogen concentration (g N kg^{-1} tissue) at TPAC19.

	Growing Degree Days (GDD) °C						
	351	467	589	662	750/850*	1595^{+}	grain
Treatment†	nitrogen concentration, g kg^{-1} tissue						
control	34.5	28.2 a‡	23.5 a	23.5 a	16.1 a	7.8 a	11.8
starter	35.6	24.8 b	18.9 b	19.1 b	14.2 b	7.4 b	12.2
P value	ns	<0.05	<0.05	<0.05	<0.05	<0.05	ns
CV	6	8	16	15	8	8	4
R^2	0.21	0.47	0.71	0.65	0.33	0.88	0.25

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking sampling dates for starter and control treatments, samples taken in two different dates. Earlier date for control and later for starter.

$^{+}$Physiological maturity.

Table 18**.** Effect of starter fertilizer differing in composition on the phosphorus concentration (g P kg^{-1} tissue) at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	265	429	528	649	775	854*	1602+	grain
Treatment†	phosphorus concentration, g kg^{-1} tissue							
control	4.4	5.3 a‡	4.5 a	3.5 a	2.8 a	2.3	0.8 a	2.6
N	4.1	4.6 b	3.5 b	2.8 b	2.4 b	2.1	0.7 b	2.5
NP	4.4	4.6 b	3.4 b	2.7 b	2.3 b	2.2	0.7 b	2.6
NPK	4.4	4.5 b	3.4 b	2.8 b	2.3 b	2.2	0.8 ab	2.6
P value	ns	<0.01	<0.001	<0.001	<0.001	ns	<0.1	ns
CV	9	13	17	17	15	13	17	8
R^2	0.21	0.24	0.55	0.46	0.31	0.33	0.02	0.02
Control vs starters	0.61	0.08	0.008	0.03	0.05	0.54	0.26	0.14

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 19**.** Effect of starter fertilizer differing in composition on the phosphorus concentration (g P kg^{-1} tissue) at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	277	454	571	649	728	845*	1529⁺	Grain
Treatment†	phosphorus concentration, g kg^{-1} tissue							
control	2.9	3.7	3.0 a‡	2.3	2.1	1.8 a	0.5	2.2
N	2.8	3.4	2.8 ab	2.3	2.0	1.6 ab	0.5	2.3
NP	2.9	3.6	2.6 bc	2.3	2.1	1.5 b	0.5	2.1
NPK	2.9	3.5	2.6 c	2.3	1.9	1.6 b	0.5	2.4
P value	ns	ns	<0.01	ns	ns	0.1	ns	ns
CV	8	9	13	9	9	17	14	12
R^2	0.19	0.35	0.65	0.3	0.03	0.59	0.31	0.28
Control vs starters	0.65	0.11	0.003	0.66	0.65	0.02	1	0.56

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

⁺Physiological maturity

Table 20**.** Effect of starter fertilizer differing in composition on the phosphorus concentration (g P kg^{-1} tissue) at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	352	446	517	619	726	825*	1657⁺	grain
Treatment†	phosphorus concentration, g kg^{-1} tissue							
control	2.5	2.7 a	2.7	2.6	2.2	2.0	0.6	2.2
N	2.6	2.3 bc	2.3	2.6	2.0	2.0	0.5	2.1
NP	2.5	2.6 ab	2.7	2.4	2.2	2.0	0.5	2.3
NPK	2.3	2.3 c	2.6	2.3	2.1	1.9	0.6	2.2
P value	ns	0.04	ns	ns	ns	ns	ns	ns
CV	15	13	16	14	15	12	24	14
R^2	0.58	0.34	0.04	0.17	0.22	0.11	0.2	0.19
Control vs starters	ns	0.03	ns	ns	ns	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

⁺Physiological maturity

Table 21**.** Effect of NP starter fertilizer on the phosphorus concentration (g P kg^{-1} tissue) at TPAC19. An LSD (α=0.1) was used to compare treatment means.

	Growing Degree Days (GDD) °C						
	351	467	589	662	750*	1595+	grain
Treatment†	nitrogen concentration, g kg^{-1} tissue						
control	6.6	4.8 a‡	3.2 a	2.6	1.6	0.5	2.4
starter	5.4	3.3 b	2.2 b	2.2	1.6	0.5	2.2
P value	ns	0.01	0.01	ns	ns	ns	ns
CV	19	27	25	18	11	15	13
R^2	0.01	0.76	0.69	0.46	0.14	0.45	0.20

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity

Table 22**.** Effect of starter fertilizer differing in composition on the potassium concentration (g K kg^{-1} tissue) at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	265	429	528	649	775	854*	1602+	grain
Treatment†	potassium concentration, g kg^{-1} tissue							
control	42.2	40.2	35.4	32.1 a‡	24.5 a	18.2	17.3	3.5
N	43.3	38.7	34.2	30.6 a	21.8 b	19.4	16.7	3.5
NP	44.3	39.3	34.0	27.8 b	21.3 b	18.4	16.4	3.6
NPK	43.7	40.2	33.7	30.4 a	20.2 b	19.1	16.5	3.6
P value	ns	ns	ns	<0.01	<0.01	ns	ns	ns
CV	5	12	10	12	15	13	9	7
R^2	0.16	0.24	0.18	0.32	0.15	0.02	0.02	0.07
Control vs starters	0.58	0.59	0.44	0.05	0.03	0.65	0.53	0.29

†Starter fertilizer treatments were: control, 3.6 kg N ha-1 and 8 kg S ha-1; N, 34 kg N ha-1 and 8 kg S ha-1; NP, N plus 7.5 kg P ha-1; and NPK, NP plus 9.5 kg K ha-1.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 23**.** Effect of starter fertilizer differing in composition on the potassium concentration (g K kg^{-1} tissue) at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	277	454	571	649	728	845*	1529^{+}	Grain
Treatment†	potassium concentration, g kg^{-1} tissue							
control	43.5	38.9 a‡	35.0 a	28.6	24.1	16.8	15.0	3.4
N	43.7	32.8 b	34.1 a	27.7	24.9	17.3	16.7	3.4
NP	40.0	33.1 b	29.5 b	29.7	22.6	16.8	15.1	3.3
NPK	44.5	30.5 b	33.4 a	29.6	24.1	16.8	15.0	3.4
P value	ns	<0.01	0.06	ns	ns	ns	ns	ns
CV	12	21	20	16	14	11	15	8
R^2	0.09	0.72	0.67	0.35	0.33	0.04	0.33	0.01
Control vs starters	0.71	<0.001	0.13	0.66	0.11	0.08	0.13	0.34

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

$^{+}$Physiological maturity.

Table 24. Effect of starter fertilizer differing in composition on the potassium concentration (g K kg^{-1} tissue) at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	352	446	517	619	726	825*	1657^{+}	grain
Treatment†	potassium concentration, g kg^{-1} tissue							
control	25.7	25.7 a‡	27.3	30.9	27.7	21.9	14.2	3.5
N	25.6	22.1 b	23.6	33.7	26.2	23.1	13.6	3.4
NP	23.1	21.5 b	23.2	31.6	24.6	21.9	13.6	3.5
NPK	26.1	20.9 b	27.3	29.4	23.8	20.9	13.1	3.4
P value	ns	0.06	ns	ns	ns	ns	ns	ns
CV	16	23	29	17	16	15	11	12
R^2	0.54	0.58	0.57	0.39	0.04	0.72	0.03	0.07
Control vs starters	ns	<0.01	ns	ns	ns	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

$^{+}$Physiological maturity.

Table 25. Effect of NP starter fertilizer on the potassium concentration (g K kg^{-1} tissue) at TPAC19.

	Growing Degree Days (GDD) °C						
	351	467	589	662	750/850*	1595^{+}	grain
Treatment†	potassium concentration, g kg^{-1} tissue						
control	41.7	31.7 a‡	22.7 a	21.7	15.9	10.0	3.8
starter	39.6	24.8 b	18.3 b	20.6	14.7	8.5	4.1
P value	ns	0.04	0.08	ns	ns	ns	ns
CV	14	29	30	25	15	26	10
R^2	0.49	0.79	0.75	0.93	0.09	0.51	0.05

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking sampling dates for starter and control treatments, samples taken in two different dates. Earlier date for control and later for starter.

$^{+}$Physiological maturity.

Table 26. Effect of starter fertilizer differing in composition on the sulfur concentration (g S kg^{-1} tissue) at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	265	429	528	649	775	854*	1602+	grain
Treatment†	sulfur concentration, g kg^{-1} tissue							
control	2.5 b‡	2.0	1.6 a	1.5 a	1.2 a	1.2 a	0.9	1.0
N	2.6 ab	1.9	1.4 b	1.3 b	1.1 b	1.1 b	0.8	1.0
NP	2.7 a	1.9	1.4 b	1.3 b	1.0 c	1.1 b	0.8	1.1
NPK	2.7 a	1.9	1.4 b	1.2 b	1.0 bc	1.1 ab	0.9	1.0
P value	0.10	ns	<0.001	<0.001	<0.001	0.08	ns	ns
CV	8	8	11	11	15	12	11	5
R^2	0.17	0.05	0.41	0.45	0.31	0.13	0.05	0.06
Control vs starters	0.02	ns	<0.001	<0.001	<0.001	0.03	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 27**.** Effect of starter fertilizer differing in composition on the sulfur concentration (g S kg^{-1} tissue) at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	277	454	571	649	728	845*	1529^{+}	Grain
Treatment†	sulfur concentration, g kg^{-1} tissue							
control	3.1 a‡	2.6	2.0 a	1.6 a	1.3	1.2 a	0.8	1.0
N	2.9 b	2.6	1.9 ab	1.5 b	1.3	1.1 b	0.9	1.0
NP	2.8 b	2.6	1.9 b	1.5 b	1.3	1.1 b	0.9	1.0
NPK	3.0 ab	2.5	1.9 b	1.5 b	1.3	1.1 b	0.8	1.0
P value	0.09	ns	<0.1	<0.1	ns	<0.05	ns	ns
CV	9	9	8	9	7	11	7	4
R^2	0.33	0.50	0.29	0.13	0.03	0.50	0.06	0.49
Control vs starters	0.03	ns	0.05	0.02	ns	<0.01	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

$^{+}$Physiological maturity.

Table 28. Effect of starter fertilizer differing in composition on the sulfur concentration (g S kg^{-1} tissue) at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	352	446	517	619	726	825*	1657^{+}	grain
Treatment†	sulfur concentration, g kg^{-1} tissue							
control	1.6	1.6	1.8	1.5	1.2	1.1	0.5	0.9
N	1.7	1.5	1.7	1.6	1.1	1.1	0.5	0.9
NP	1.7	1.5	1.8	1.4	1.2	1.0	0.5	0.9
NPK	1.6	1.5	1.9	1.4	1.1	1.1	0.6	0.9
P value	ns	ns	ns	ns	ns	ns	ns	ns
CV	9	11	14	16	11	11	10	8
R^2	0.24	0.68	0.02	0.04	0.10	0.20	0.06	0.19
Control vs starters	ns	ns	ns	ns	ns	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

$^{+}$Physiological maturity.

Table 29**.** Effect of NP starter fertilizer on the potassium concentration (g K kg^{-1} tissue) at TPAC19.

	Growing Degree Days (GDD) °C						
	351	467	589	662	750/850*	1595^+	grain
Treatment†	potassium concentration, g kg^{-1} tissue						
control	2.8	1.9 a‡	1.5 a	1.5 a	0.9	0.5 a	0.9
starter	2.6	1.5 b	1.1 b	1.2 b	0.9	0.4 b	0.8
P value	ns	<0.01	<0.01	<0.01	ns	0.07	ns
CV	10	12	19	16	8	11	8
R^2	0.1	0.72	0.76	0.87	0.19	0.53	0.20

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking sampling dates for starter and control treatments, samples taken in two different dates. Earlier date for control and later for starter.

$^+$Physiological maturity.

Table 30**.** Effect of starter fertilizer differing in composition on nitrogen content in above-ground plant dry matter at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	265	429	528	649	775	854*	1602$^+$	grain
Treatment†	nitrogen content, kg ha^{-1}							
control	0.8 b‡	4.5 c	8.5 c	21.9 b	37.3 b	47.7	34.2	112.9 c
N	1.2 a	6.7 b	12.1 b	26.3 a	42.1 a	47.5	32.5	120.8 ab
NP	1.3 a	7.5 a	13.3 a	27.4 a	39.8 ab	47.5	31.7	124.8 a
NPK	1.2 a	7.5 a	12.7 ab	26.2 a	39.3 ab	50.2	32.3	116.4 bc
P value	<0.001	<0.001	<0.001	<0.01	<0.1	ns	ns	<0.01
CV	31	26	23	19	12	12	15	8
R^2	0.38	0.51	0.57	0.32	0.15	0.07	0.17	0.33
Control vs starters	<0.001	<0.001	<0.001	<0.001	0.05	ns	ns	<0.01

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

$^+$Physiological maturity.

Table 31. Effect of starter fertilizer differing in composition on phosphorus content at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	265	429	528	649	775	854*	1602+	grain
Treatment†	phosphorus content, kg ha^{-1}							
control	0.11	1.0 b‡	2.0 b	3.5 b	5.9	6.4 c	3.1	22.3
N	0.14	1.3 a	2.4 a	4.2 a	6.6	6.7 bc	2.8	23.3
NP	0.14	1.4 a	2.6 a	4.0 a	6.4	7.4 ab	2.7	24.5
NPK	0.14	1.4 a	2.5 a	4.1 a	6.3	7.7 a	2.9	23.2
P value	ns	<0.001	<0.01	<0.01	ns	<0.01	ns	ns
CV	28	22	20	18	15	17	19	10
R^2	0.19	0.29	0.32	0.29	0.10	0.20	0.04	0.17
Control vs starters	0.02	<0.001	<0.001	<0.01	0.07	<0.01	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 32**.** Effect of starter fertilizer differing in composition on potassium content at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	265	429	528	649	775	854*	1602+	grain
Treatment†	potassium content, kg ha^{-1}							
control	1.1 b‡	7.7 c	15.7 b	32.2 b	50.8 b	51.2 b	65.1	30.7 c
N	1.4 a	10.6 b	23.6 a	45.9 a	58.7 a	61.8 a	66.6	33.1 ab
NP	1.5 a	12.3 a	26.0 a	41.5 a	60.4 a	64.3 a	62.4	34.4 a
NPK	1.4 a	12.3 a	24.5 a	44.9 a	54.8 ab	65.2 a	60.7	32.1 bc
P value	<0.05	<0.001	<0.001	<0.001	<0.1	<0.01	ns	<0.01
CV	29	27	28	23	17	21	17	11
R^2	0.19	0.48	0.60	0.44	0.06	0.21	0.02	0.16
Control vs starters	<0.01	<0.001	<0.001	<0.001	0.03	<0.01	ns	<0.01

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 33. Effect of starter fertilizer differing in composition on sulfur content at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	265	429	528	649	775	854*	1602+	grain
Treatment†	sulfur content, kg ha^{-1}							
control	0.06 b‡	0.38 b	0.69 b	1.46 b	2.54 b	3.2 b	3.4	9.0 b
N	0.09 a	0.53 a	0.97 a	1.93 a	2.96 a	3.3 b	3.3	9.7 a
NP	0.09 a	0.58 a	1.04 a	1.88 a	2.82 a	3.5 ab	3.2	9.9 a
NPK	0.08 a	0.58 a	0.97 a	1.83 a	2.76 ab	3.7 a	3.3	9.0 b
P value	<0.05	<0.001	<0.001	<0.001	<0.05	<0.01	ns	<0.01
CV	29	24	21	19	14	15	16	9
R^2	0.19	0.42	0.57	0.37	0.19	0.12	0.18	0.16
Control vs starters	<0.01	<0.001	<0.001	<0.001	0.01	<0.01	ns	<0.01

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 34. Effect of starter fertilizer differing in composition on nitrogen content at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	277	454	571	649	728	845*	1529+	Grain
Treatment†	nitrogen content, kg ha^{-1}							
control	0.9 b‡	9.6 b	29.4	41.9	54.1	71.3	38.5	119.1
N	1.2 a	12.4 a	33.1	45.1	48.2	72.5	39.1	122.7
NP	1.2 a	14.2 a	33.8	41.7	55.4	72.9	37.3	113.2
NPK	1.3 a	13.1 a	33.9	39.1	53.6	72.8	36.3	120.5
P value	<0.05	<0.05	ns	ns	ns	ns	ns	ns
CV	27	26	19	15	11	14	10	8
R^2	0.22	0.35	0.44	0.54	0.45	0.08	0.06	0.16
Control vs starters	<0.01	<0.01	0.05	ns	ns	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 35. Effect of starter fertilizer differing in composition on phosphorus content at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	277	454	571	649	728	845*	1529⁺	Grain
Treatment†	phosphorus content, kg ha^{-1}							
control	0.08	1.05 c‡	2.85	3.97	5.48	7.29	2.06	21.94
N	0.08	1.28 b	3.24	4.45	5.86	7.52	2.17	23.16
NP	0.09	1.53 a	3.16	4.21	5.88	7.44	2.01	20.58
NPK	0.10	1.44 ab	3.10	3.97	5.74	7.57	2.06	24.06
P value	ns	<0.01	ns	ns	ns	ns	ns	ns
CV	25	23	15	13	11	18	16	16
R^2	0.08	0.42	0.05	0.39	0.16	0.29	0.39	0.34
Control vs starters	ns	<0.01	ns	ns	ns	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

⁺Physiological maturity.

Table 36**.** Effect of starter fertilizer differing in composition on potassium content at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	277	454	571	649	728	845*	1529+	Grain
Treatment†	potassium content, kg ha^{-1}							
control	1.2 b‡	11.4	34.2	49.6	69.9	76.3	69.4	32.1
N	1.2 b	12.6	39.5	55.8	73.3	80.0	68.6	33.9
NP	1.2 b	14.3	36.9	53.8	64.6	81.6	60.3	31.6
NPK	1.5 a	12.8	40.4	51.8	69.6	81.2	60.2	34.5
P value	<0.1	ns	ns	ns	ns	ns	ns	ns
CV	23	31	29	22	19	15	21	12
R^2	0.17	0.44	0.52	0.39	0.21	0.32	0.35	0.24
Control vs starters	ns	ns	ns	ns	ns	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 37. Effect of starter fertilizer differing in composition on sulfur content at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	277	454	571	649	728	845*	1529⁺	Grain
Treatment†	sulfur content, kg ha^{-1}							
control	0.08	0.75 b‡	1.91	2.74	3.59	4.89	3.37	9.58
N	0.09	0.98 a	2.21	2.86	3.93	4.87	3.51	9.85
NP	0.10	1.11 a	2.24	2.66	3.82	5.11	3.43	9.66
NPK	0.11	1.03 a	2.24	2.56	3.72	5.11	3.37	9.98
P value	ns	<0.01	ns	ns	ns	ns	ns	ns
CV	24	25	15	13	11	15	9	8
R^2	0.05	0.35	0.12	0.53	0.28	0.02	0.26	0.27
Control vs starters	ns	<0.01	0.02	ns	ns	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

⁺Physiological maturity.

Table 38. Effect of starter fertilizer differing in composition on nitrogen content at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	352	446	517	619	726	825*	1657+	grain
Treatment†	nitrogen content, kg ha^{-1}							
control	6.9 c†	15.3	29.8	53.4	100.1	112.9	67.8 a	105.1
N	6.7 c	14.5	29.5	53.3	92.9	108.1	60.9 b	102.6
NP	10.5 a	14.1	31.3	46.3	89.6	114.6	59.2 b	106.3
NPK	8.4 b	16.9	33.3	49.3	89.6	117.6	59.5 b	105.1
P value	<0.001	ns	ns	ns	ns	ns	<0.01	ns
CV	25	26	24	25	23	15	15	10
R^2	0.73	0.36	0.35	0.16	0.69	0.23	0.43	0.31
Control vs starters	<0.01	ns	ns	ns	0.09	ns	<0.01	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 39. Effect of starter fertilizer differing in composition on phosphorus content at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	352	446	517	619	726	825*	1657⁺	grain
Treatment†	phosphorus content, kg ha^{-1}							
control	0.8 b‡	1.5	3.1 a	5.9	10.9	13.1	5.4	20.3
N	0.7 b	1.4	2.5 b	5.4	9.7	12.4	4.6	18.5
NP	1.1 a	1.5	3.1 a	5.3	10.1	13.9	4.2	20.1
NPK	0.8 b	1.6	3.3 a	5.5	10.5	12.9	4.8	19.0
P value	<0.05	ns	<0.05	ns	ns	ns	ns	ns
CV	20	23	22	19	15	19	28	18
R^2	0.40	0.02	0.45	0.15	0.56	0.20	0.36	0.01
Control vs starters	ns	ns	ns	ns	0.1	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

⁺Physiological maturity.

Table 40. Effect of starter fertilizer differing in composition on potassium content at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	352	446	517	619	726	825*	1657⁺	grain
Treatment†	potassium content, kg ha^{-1}							
control	8.1 bc‡	14.7	30.8	70.1	137.9	147.5	138.1	31.9
N	7.3 c	13.1	25.3	71.9	131.4	145.1	125.7	29.9
NP	9.6 a	12.6	27.9	68.1	115.9	153.3	116.1	31.5
NPK	8.9 ab	14.5	34.9	69.9	124.9	142.6	114.8	29.6
P value	<0.05	ns	ns	ns	ns	ns	ns	ns
CV	25	32	36	22	25	13	19	17
R^2	0.58	0.44	0.47	0.44	0.54	0.17	0.22	0.30
Control vs starters	ns	ns	ns	ns	ns	ns	<0.01	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

⁺Physiological maturity.

Table 41. Effect of starter fertilizer differing in composition on sulfur content at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Growing Degree Days (GDD) °C							
	352	446	517	619	726	825*	1657+	grain
Treatment†	sulfur content, kg ha^{-1}							
control	0.5 bc†	0.9	2.1 ab	3.4	5.8	7.1	5.2 a	7.9
N	0.5 c	0.9	1.9 b	3.4	5.6	6.7	4.6 b	7.9
NP	0.7 a	0.9	2.1 ab	3.0	5.6	7.4	4.6 b	7.9
NPK	0.6 b	1.0	2.4 a	3.3	5.7	7.3	4.9 ab	7.9
P value	<0.001	ns	<0.1	ns	ns	ns	<0.01	ns
CV	21	24	23	20	16	19	13	10
R^2	0.59	0.25	0.44	0.02	0.57	0.20	0.39	0.37
Control vs starters	0.04	ns	ns	ns	ns	ns	<0.01	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking.

+Physiological maturity.

Table 42. Effect of NP starter fertilizer on nitrogen content at TPAC19.

	Growing Degree Days (GDD) °C						
	351	467	589	662	750/850*	1595[+]	grain
Treatment†	nitrogen content, kg ha^{-1}						
control	3.7	10.1 b‡	19.4 b	32.7	55.8	35.1	118.9
starter	7.4	18.7 a	29.2 a	39.9	48.9	32.4	123.5
P value	ns	<0.001	<0.01	ns	ns	ns	ns
CV	58	42	23	21	12	12	9
R^2	0.17	0.94	0.81	0.41	0.29	0.28	0.51

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking sampling dates for starter and control treatments, samples taken in two different dates. Earlier date for control and later for starter.

[+]Physiological maturity.

Table 43. Effect of NP starter fertilizer on phosphorus content at TPAC19.

	Growing Degree Days (GDD) °C						
	351	467	589	662	750/850*	1595^{+}	grain
Treatment†	phosphorus content, kg ha^{-1}						
control	0.7	1.7 b‡	2.6 b	3.6	6.2	2.4	24.1
starter	1.1	2.4 a	3.5 a	4.8	5.0	2.2	23.2
P value	ns	<0.001	<0.05	ns	ns	ns	ns
CV	42	28	21	24	19	17	19
R^2	0.01	0.88	0.68	0.32	0.10	0.55	0.58

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking sampling dates for starter and control treatments, samples taken in two different dates. Earlier date for control and later for starter.

$^{+}$Physiological maturity.

Table 44. Effect of NP starter fertilizer on potassium content at TPAC19.

	Growing Degree Days (GDD) °C						
	351	467	589	662	750/850*	1595+	grain
Treatment†	potassium content, kg ha^{-1}						
control	4.2	12.3 b‡	19.7 b	29.8 b	57.9	44.9	40.3
starter	8.6	19.3 a	29.4 a	47.6 a	48.7	37.8	38.5
P value	ns	<0.05	<0.10	<0.05	ns	ns	ns
CV	62	56	45	49	20	30	17
R^2	0.11	0.9	0.71	0.84	0.14	0.43	0.72

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking sampling dates for starter and control treatments, samples taken in two different dates. Earlier date for control and later for starter.

+Physiological maturity.

Table 45. Effect of NP starter fertilizer on sulfur content at TPAC19.

	Growing Degree Days (GDD) °C						
	351	467	589	662	750/850*	1595⁺	grain
Treatment†	sulfur content, kg ha^{-1}						
control	0.3	0.7 b‡	1.3 b	2.1	3.4 a	2.4	8.8
starter	0.5	1.2 a	1.7 a	2.4	2.8 b	2.1	8.3
P value	ns	<0.001	<0.01	ns	<0.1	ns	ns
CV	49	38	19	19	13	15	14
R^2	0.07	0.96	0.71	0.21	0.20	0.35	0.57

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

*Tasseling and/or silking sampling dates for starter and control treatments, samples taken in two different dates. Earlier date for control and later for starter.

⁺Physiological maturity.

Table 46. Effect of starter fertilizer differing in composition on the percentage of plants tasseling and/or silking at SEPAC and NEPAC in 2019 and 2020. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Location			
	SEPAC19	NEPAC19	SEPAC20	NEPAC20
Treatment†	% of plants tasseling and/or silking			
control	40 b‡	87 b	79 b	41 b
N	91 a	95 a	95 a	42 b
NP	90 a	98 a	90 a	55 ab
NPK	88 a	95 a	91 a	61 a
P value	<0.001	<0.001	<0.01	0.1
CV	32	6	10	35
R^2	0.82	0.68	0.51	0.16
Control vs starters	<0.001	<0.01	<0.001	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 47. Effect of NP starter fertilizer on the percentage of plants tasseling and/or silking at TPAC in 2019 and 2020.

	Location	
	TPAC19	TPAC20
Treatment†	% of plants tasseling and/or silking	
control	0 b‡	47 b
starter	11 a	94 a
P value	<0.01	<0.01
CV	1.4	38
R^2	0.5	0.87

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 48. Effect of starter fertilizer differing in composition on the final number of leaves per plant at SEPAC and NEPAC in 2019 and 2020. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Location			
	SEPAC19	NEPAC19	SEPAC20	NEPAC20
Treatment†	No. leaves			
control	17.7 b‡	16.4 b	17.8 c	19.2
N	18.6 a	17.2 a	18.2 b	18.7
NP	18.8 a	17.2 a	18.2 b	19.0
NPK	18.7 a	17.1 a	18.3 a	19.1
P value	<0.001	<0.001	<0.001	ns
CV	3	2	1	39
R^2	0.71	0.80	0.84	0.13
Control vs starters	<0.001	<0.001	<0.001	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 49. Effect of NP starter fertilizer on the final number of leaves per plant at TPAC in 2019 and 2020.

	Location	
	TPAC19	TPAC20
Treatment†	No. leaves	
control	15.9	15.3 b‡
starter	16.7	17.8 a
P value	> 0.1	<0.001
CV	5	8
R^2	0.27	0.89

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 50. Effect of starter fertilizer differing in composition on the subtending ear leaf number at SEPAC and NEPAC in 2019 and 2020. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Location			
	SEPAC19	NEPAC19	SEPAC20	NEPAC20
Treatment†	Subtending ear leaf number			
control	12.8 c‡	10.6 b	12.2 c	12.4
N	12.9 b	11.4 a	12.5 b	12.4
NP	13.1 a	11.5 a	12.4 b	12.4
NPK	13.0 ab	11.3 a	12.6 a	12.4
P value	<0.001	<0.01	<0.001	ns
CV	1	5	1	1
R^2	0.54	0.62	0.89	0.15
Control vs starters	ns	<0.01	<0.001	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 51. Effect of NP starter fertilizer on the subtending ear leaf number at TPAC in 2019 and 2020.

	Location	
	TPAC19	TPAC20
Treatment†	Subtending ear leaf number	
control	12.1 b‡	12.1a
starter	12.3 a	11.8 b
P value	<0.1	<0.01
CV	2	1
R^2	0.55	0.71

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 52. Effect of starter fertilizer differing in composition on the grain yield and moisture at SEPAC and NEPAC in 2019 and 2020. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

	Location			
	SEPAC19	NEPAC19	SEPAC20	NEPAC20
Treatment†	Yield, kg ha^{-1}			
control	8628 b‡	10899	10707 b	10440
N	9340 a	11088	11212 a	10031
NP	9652 a	11340	11172 a	10028
NPK	9513 a	11277	11073 a	10056
P value	<0.01	ns	<0.001	ns
CV	7	3	3	6
R^2	0.47	0.23	0.66	0.76
Control vs starters	<0.01	ns	<0.001	ns
	Moisture, g kg^{-1}			
control	230 a	196	256 a	226
N	213 b	191	254 ab	222
NP	214 b	191	254 ab	222
NPK	214 b	190	251 b	218
P value	<0.001	ns	0.05	ns
CV	4	2	3	3
R^2	0.67	0.18	0.85	0.10
Control vs starters	<0.001	ns	0.02	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 53**.** Effect of NP starter fertilizer on grain yield and grain moisture content at TPAC in 2019 and 2020.

	Location	
	TPAC19	TPAC20
Treatment†	Yield, kg ha^{-1}	
control	12159 b‡	13182
starter	13293 a	13230
P value	<0.001	ns
CV	6	2
R^2	0.85	0.72
	Moisture, g kg^{-1}	
control	228 a	189 a
starter	215 b	179 a
P value	<0.001	<0.001
CV	3	3
R^2	0.89	0.96

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 54. Effect of starter fertilizer differing in composition on the number of rows per ear, kernels per row and weight of 1000 kernels at SEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

Treatment	Rows ear^{-1}	Kernels row^{-1}	Weight 1000 kernel, g
control	15.5	28.2	298.8
N	16.7	28.9	294.2
NP	16.6	28.2	301.5
NPK	16.8	28.4	299.1
P value	ns	ns	ns
CV	3	6	5
R^2	0.001	0.05	0.06
Control vs starters	0.24	0.99	0.86

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 55. Effect of starter fertilizer differing in composition on the number of rows per ear, kernels per row and weight of 1000 kernels at NEPAC19. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

Treatment	Rows ear^{-1}	Kernels row^{-1}	Weight 1000 kernel, g
control	15.1	37.3	293.7
N	15.0	36.3	284.7
NP	15.1	36.4	282.1
NPK	14.9	36.3	280.7
P value	ns	ns	ns
CV	2	3	5
R^2	0.04	0.03	0.20
Control vs starters	ns	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 56. Effect of NP starter fertilizer on the number of rows per ear, kernels per row and weight of 1000 kernels at TPAC19.

Treatment	Row ear^{-1}	Kernel row^{-1}	Weight 1000 kernel, g
control	14.8	33.7	318.1
starter	14.6	33.2	314.3
P value	> 0.1	> 0.1	> 0.1
CV	2	4	2
R^2	0.67	0.54	0.57

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 57. Effect of starter fertilizer differing in composition on the number of rows per ear, kernels per row and weight of 1000 kernels at SEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

Treatment	Rows ear^{-1}	Kernels row^{-1}	Weight 1000 kernel, g
control	17.0 b‡	30.8	312.1
N	17.6 a	32.1	310.1
NP	17.8 a	31.8	310.6
NPK	17.8 a	32.6	312.1
P value	<0.001	ns	ns
CV	3	7	4
R^2	0.31	0.10	0.17
Control vs starters	<0.001	ns	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 58. Effect of starter fertilizer differing in composition on the number of rows per ear, kernels per row and weight of 1000 kernels at NEPAC20. An LSD (α=0.1) and a single-degree-of-freedom contrast (α=0.1; control vs mean of 3 starter treatments) were used to compare treatment means.

Treatment	Rows ear^{-1}	Kernels row^{-1}	Weight 1000 kernel, g
control	14.9	39.4 a‡	293.3
N	14.7	36.6 b	286.1
NP	14.7	37.2 b	281.8
NPK	14.5	35.8 b	288.7
P value	ns	<0.05	ns
CV	3	8	6
R^2	0.15	0.59	0.32
Control vs starters	ns	<0.01	ns

†Starter fertilizer treatments were: control, 3.6 kg N ha^{-1} and 8 kg S ha^{-1}; N, 34 kg N ha^{-1} and 8 kg S ha^{-1}; NP, N plus 7.5 kg P ha^{-1}; and NPK, NP plus 9.5 kg K ha^{-1}.
‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

Table 59. Effect of NP starter fertilizer on the number of rows per ear, kernels per row and weight of 1000 kernels at TPAC20.

Treatment	Rows ear^{-1}	Kernels row^{-1}	Weight 1000 kernel, g
control	14.8	40.3	290.1
starter	14.9	42.1	292.3
P value	ns	<0.05	ns
CV	2	3	3
R^2	0.81	0.62	0.44

†Starter fertilizer treatments were: control, no fertilizer added; starter, 46 kg N ha^{-1} and 18 kg P ha^{-1}

‡Means in a column followed by the same letter do not differ as assessed by LSD (α=0.1).

APPENDIX

Table A-1. Air temperature (°C) and precipitation (mm) monthly average from 2019 and 2020 for all sites where starter fertilizer studies were conducted.

	Temperature, °C		Precipitation, mm	
	2019	2020	2019	2020
Month	SEPAC			
April	13.8 (+1.0)	11.4 (-1.4)	16.9 (+5.5)	8.3 (-3.1)
May	19.2 (+1.6)	16.6 (-1.1)	15.4 (+2.6)	9.2 (-3.5)
June	21.3 (-1.1)	22.5 (+0.2)	22.9 (+12.0)	6.4 (-4.6)
July	24.8 (+0.7)	25.2 (+1.1)	4.5 (-7.0)	8.9 (-2.6)
August	23.4 (-0.1)	22.7 (-0.7)	11.1 (+0.2)	10.3 (-0.6)
September	22.9 (+3.4)	19.3 (-0.2)	0.3 (-7.6)	2.6 (-5.4)
October	15.3 (+1.8)	13.3 (-0.2)	13.2 (+4.0)	14.7 (+5.4)
	NEPAC			
April	9.0 (-0.2)	6.5 (-2.7)	12.1 (+2.8)	5.5 (-3.8)
May	14.9 (-0.1)	13.9 (-1.1)	11.5 (+0.5)	12.7 (+1.8)
June	20.1 (-0.3)	20.6 (+0.2)	9.8 (-1.6)	7.3 (-4.0)
July	24.1 (+1.8)	23.6 (+1.4)	10.8 (+0.5)	4.9 (-5.5)
August	21.4 (+0.1)	22.0 (+0.7)	15.7 (+6.0)	10.7 (+0.9)
September	19.8 (+2.5)	16.8 (-0.5)	9.0 (+0.9)	2.7 (-5.3)
October	12.1 (+1.3)	9.7 (-1.1)	7.8 (+0.2)	8.6 (+1.0)
	TPAC			
April	9.5 (-1.3)	9.9 (-0.9)	15.1 (+6.5)	8.3 (-0.4)
May	15.5 (-1.1)	16.2 (-0.4)	12.9 (+1.1)	8.3 (-3.5)
June	21.2 (-0.6)	23.4 (+1.6)	9.7 (-1.8)	9.9 (-1.7)
July	24.6 (+1.3)	24.7 (+1.4)	7.4 (-3.0)	11.3 (+1.0)
August	21.9 (-0.5)	22.1 (-0.3)	8.4 (-1.6)	7.8 (-2.2)
September	21.1 (+2.3)	18.2 (-0.6)	6.2 (-0.9)	4.9 (-2.2)
October	12.8 (+0.7)	11.6 (-0.5)	10.2 (+3.4)	6.8 (-0.1)

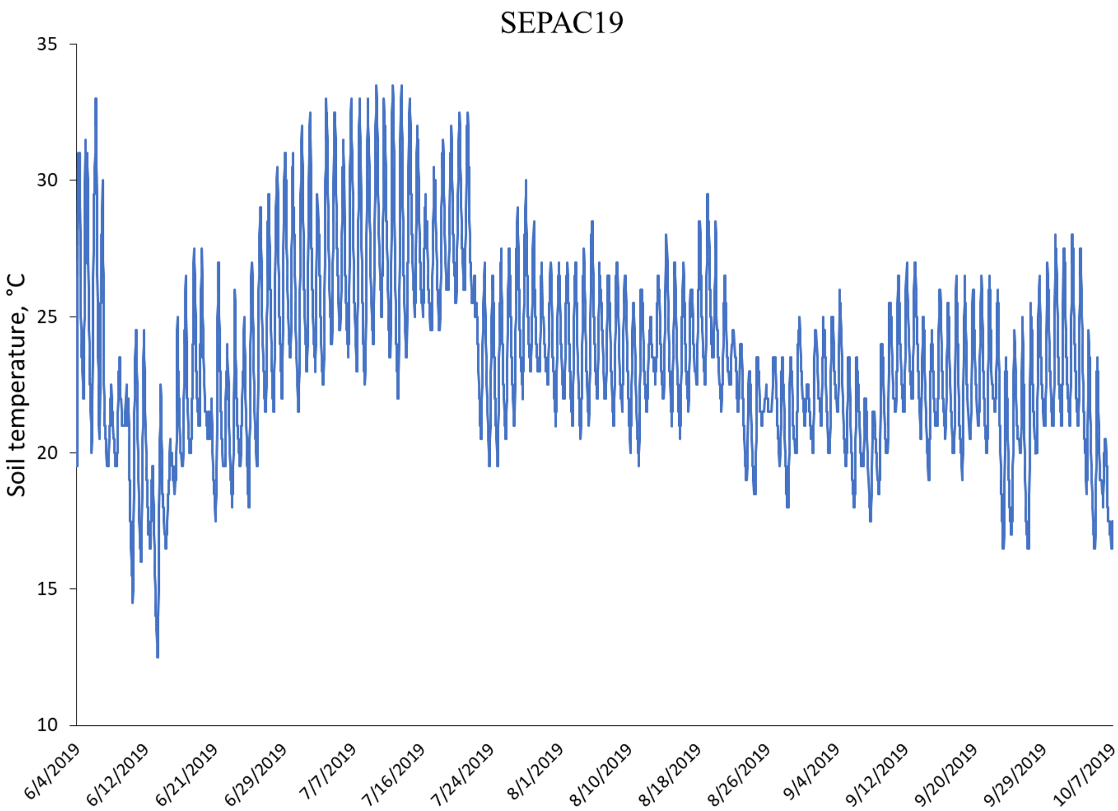

Figure 1. SEPAC19 soil temperature values during the growing season. Soil temperature was measured at a depth of 5 cm in the planted row. Soil maximum and minimum daily temperature are plotted.

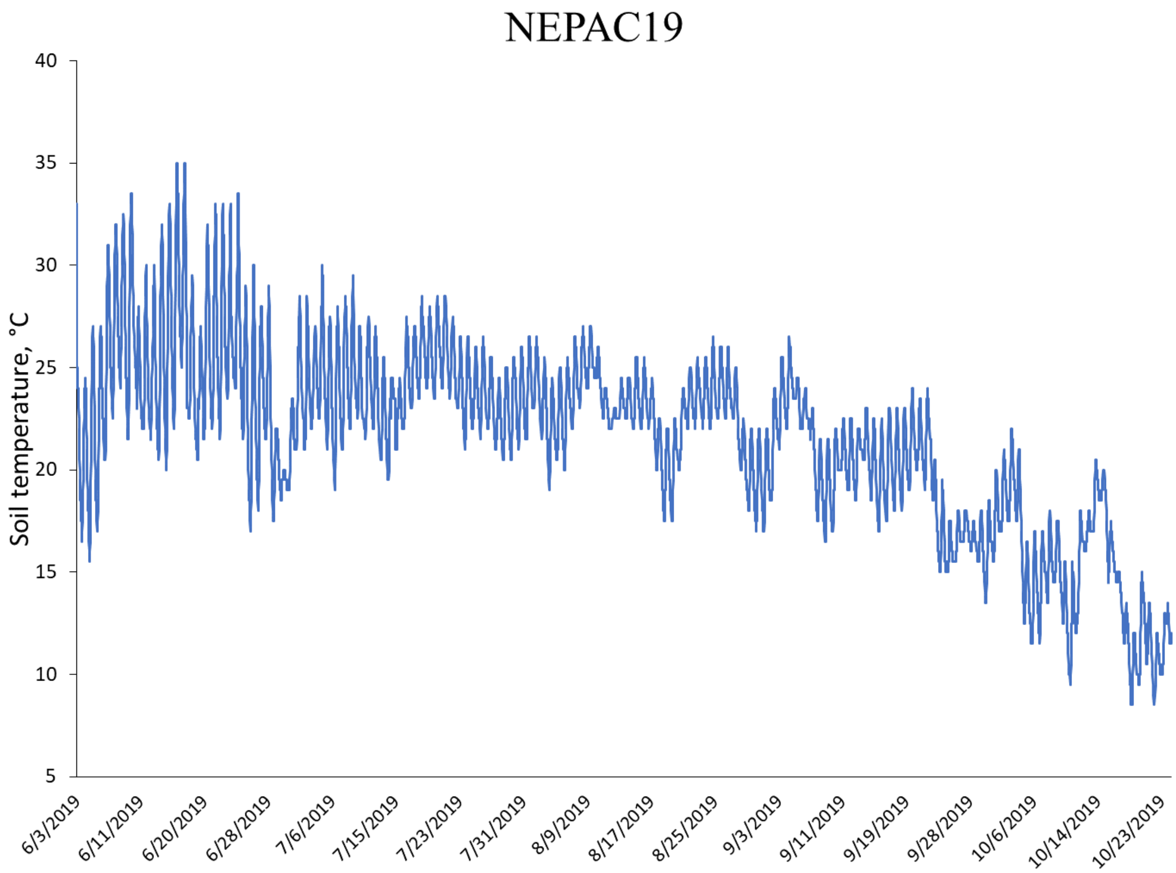

Figure 2. NEPAC19 soil temperature values during the growing season Soil temperature was measured at a depth of 5 cm in the planted row. Soil maximum and minimum daily temperature are plotted.

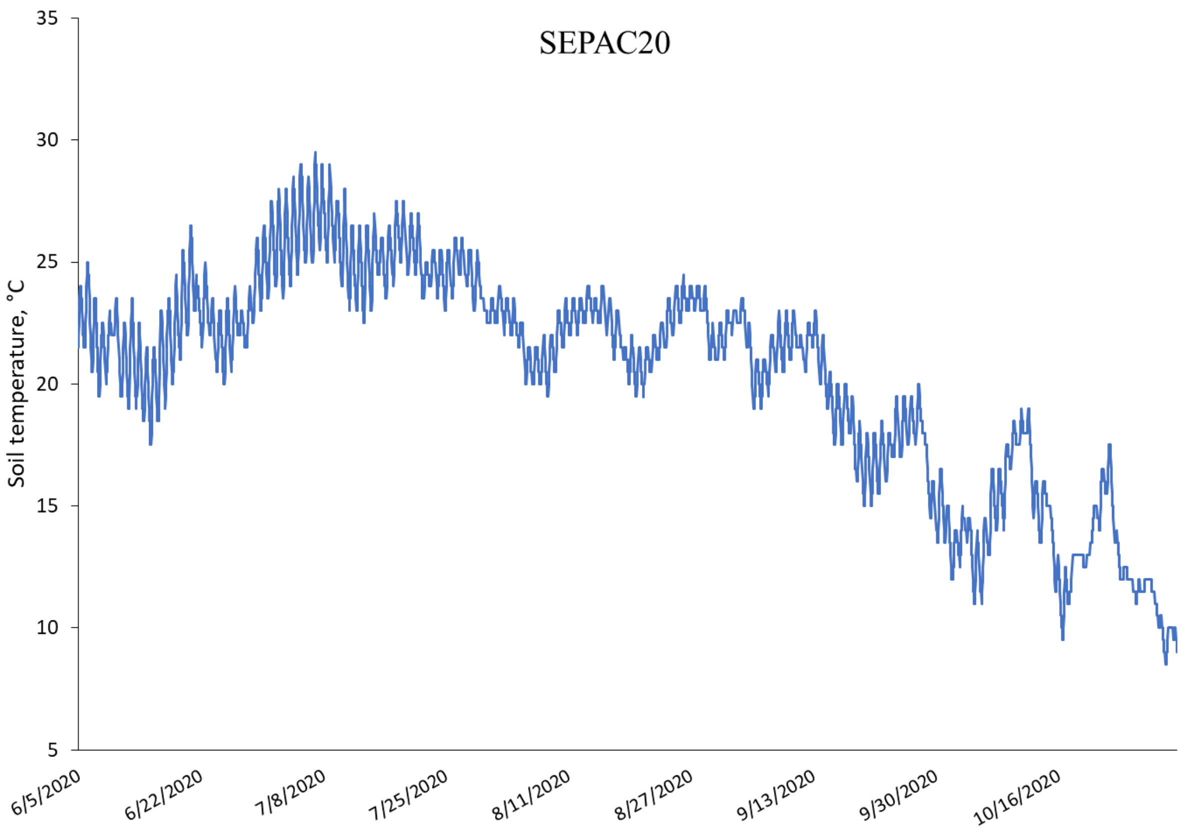

Figure 3. SEPAC20 soil temperature values during the growing season. Soil temperature was measured at a depth of 5 cm in the planted row. Soil maximum and minimum daily temperature are plotted.

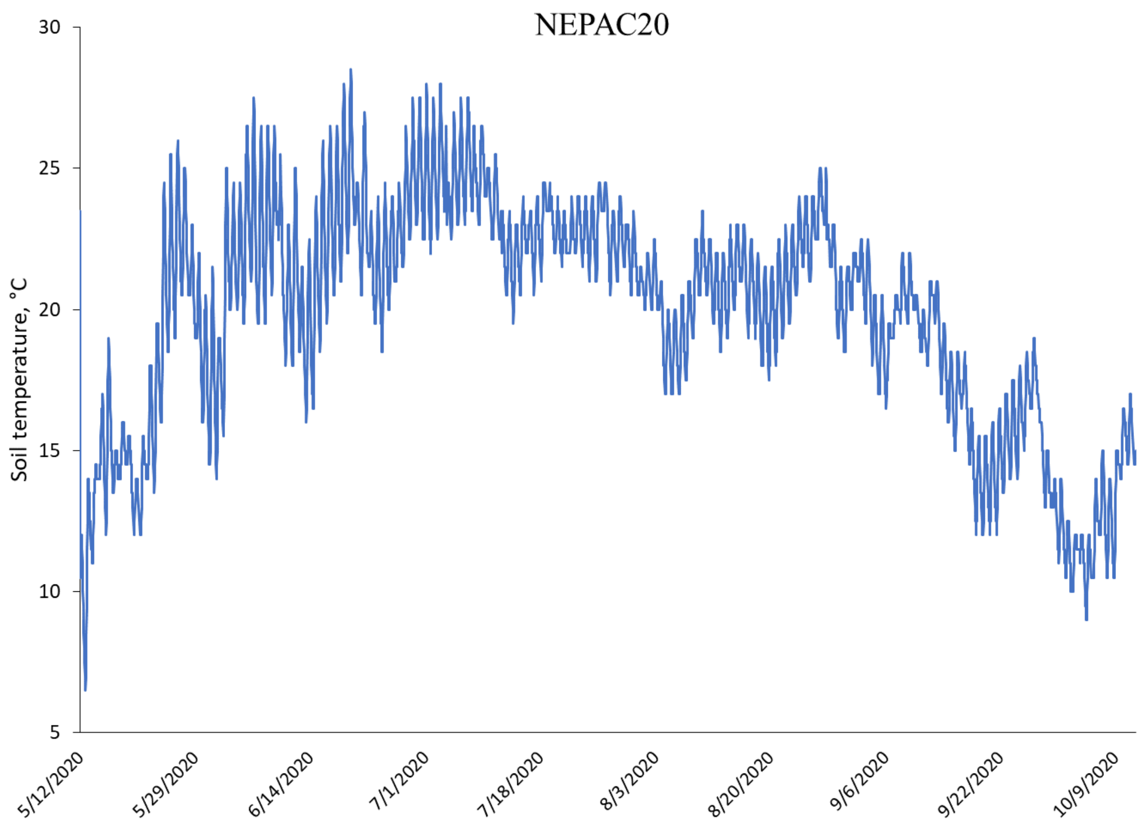

Figure 4. NEPAC20 soil temperature values during the growing season. Soil temperature was measured at a depth of 5 cm in the planted row. Soil maximum and minimum daily temperature are plotted.

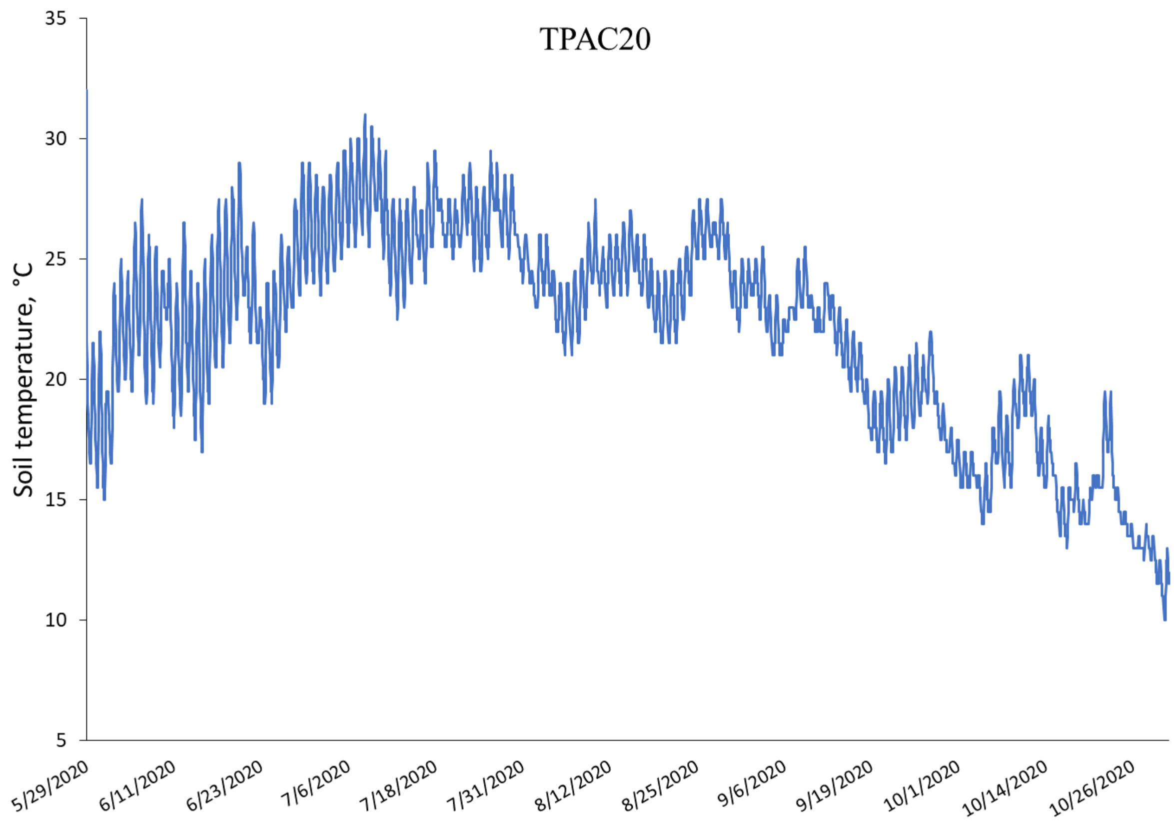

Figure 5. TPAC20 soil temperature values during the growing season. Soil temperature was measured at a depth of 5 cm in the planted row. Soil maximum and minimum daily temperature are plotted.

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