CHANGING SOIL FERTILITY STRATEGIES TO ADDRESS NEW CHALLENGES IN SOYBEAN N FIXATION AND SUGARBEET MANAGEMENT

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ABSTRACT

Michigan spring weather variabilities and earlier planting dates may provide opportunities for starter fertilizer to influence early-season soybean (*Glycine max* L. Merr.) dry matter production while simultaneously decreasing the time interval for nutrient accumulation. However, potential fertilizer impacts on inhibition of biological N fixation (BNF) are not well understood. Two multi-year field trials investigated the effects of planting date, starter fertilizer, and various nitrogen (N) application timings on BNF, grain yield, and expected net return on irrigated and non-irrigated environments. April planting as compared to May increased grain yield in only one of four site years. Starter fertilizers containing < 28 kg N ha^{-1} did not negatively influence BNF, while treatments containing 112 kg N ha^{-1} saw significant BNF contribution reductions. Grain yield was influenced by fertilizer strategy in one of four site years, but none of the evaluated fertilizer treatments exceeded profitability of the non-treated control.

Over-winter climate variability in Michigan has become an unpredictable freeze-thaw cycle that impedes the viability of sugarbeets stored in outdoor piles. Adjusting cultural and nutrient management of both early and regular harvest timings may generate greater sucrose production with less overall tonnage. Two multi-year field trials were established to evaluate two opposing cultivars, two N rates, and liquid potassium on early and conventional harvest timings. A high tonnage cultivar produced greater yield and recoverable sucrose during early harvest than a cultivar with moderate tonnage levels but good disease resistance. Sucrose and tonnage were maximized by the split-applied (179 kg ha^{-1}) N rate for both harvest timings in both site years. Surface-banded liquid potassium applied in early July did not influence yield or recoverable sucrose in either site year. Further research is supported by the interaction of cultivar selection, N rate, and harvest timing.

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CHAPTER 1: LITERATURE REVIEW

Global Soybean Demand and Regional Production

Grain quality attributes have allowed soybean (*Glycine max* (L.) Merr.) to become one of the most traded commodities in the world. Soybean seed has the highest protein (~40%) and gross vegetable oil content (~20%) of any cultivated crop (Singh, 2010). The origin of soybean cultivation can be traced back 3700 years to China and eastern Russia (Singh, 2010). Human consumption of soy protein accounts for only 2% of production, while the remaining 98% is processed into soybean meal for livestock (Goldsmith, 2008). From 1907 to 1925, soybean production in the United States grew from 123,550 to nearly 4,942,100 hectares (USDA-NASS, 2021). At that time, soybean was primarily grown for forage, with only 25% of the total area harvested for dry grain in 1925. In 1941, the area harvested for grain surpassed that of forage (Strand, 1948).

Current soybean acreage exceeded 203 million hectares in 2020 (USDA-NASS, 2021). Mechanization such as planting and harvesting equipment and the dependability of soybeans to yield well under a variety of conditions aided the expansion of acreage (Morse et al. 1950). Soybeans can be grown across a range of soil properties, including those considered to be unproductive for corn (*Zea mays* L.) with respect to soil texture, pH, CEC, and topography (Kravchenko & Bullock, 2000)

North and South America produce 80% of the world’s soybeans, with global production utilizing around 6% of the world’s arable land (Goldsmith, 2008). From 1961 to 2006 soybean area harvested in the United States and China combined decreased by over 39 million hectares, while Brazil and Argentina combined increased their harvested soybean area by 37 million hectares (Masuda & Goldsmith, 2009). China and Mexico were the two largest export destinations for US soybeans in 2019 at a value of US$7.989 and $1.867 billion, respectively. Soybean production in the U.S. totaled 96.83 million metric tons in 2019, down from 123.55 million metric tons in 2018 (USDA-NASS, 2018). The average yield was 2.98 metric tons per hectare on ~30.3 million hectares. The U.S. produced 28% of the global soybeans in 2019, with Brazil, Argentina, and China producing 37%, 16%, and 5%, respectively (USDA-NASS, 2019).

Michigan soybean production has increased from 861,980 hectares in 2001 to 926,730 hectares in 2021. The increase in soybean acres in recent years is likely due to changes in profitability when compared to high input costs associated with corn production (Schnitkey, 2017). Due to the varying soil orders and textural classes across Michigan, soybeans tend to be grown on less productive ground as higher-value crops can be grown in better-producing fields and regions.

Planting Date

Practitioners' final decision regarding seed is planting date, but environmental conditions can narrow or widen the planting window considerably from one year to another (Egli & Cornelius, 2009; Kane et al., 1997). Nelson (2021) assessed the response of various maturity cultivars on planting dates across multiple states and observed planting a late-maturity soybean cultivar in mid-April increased yield by four bushels per acre. Yields decline as planting date is delayed into June, regardless of soybean cultivar. (Egli & Cornelius, 2009; Johnson, 1987; Caldwell & Howell, 1973; Siler, 2020; Norman, 2012). Previous research found yield decreased 39.0 kg ha^{-1} d^{-1} for every day planting was delayed after 1 May, through the first week of July (Hankinson et al., 2015). Similarly, Siler (2020) reported a daily yield decline of 12.9 kg ha^{-1} d^{-1} between mid-May and early-June planting dates, and 30.3 kg ha^{-1} d^{-1} decline between early June and late June (Siler, 2020). De Bruin & Pedersen, (2008) suggested that an April planting date did not limit plant establishment due to a lack of significant difference in plant stand for April, May, and June planting dates. Robinson et al. (2009) measured soybean yield across a range of planting dates from late March until early June in Indiana and observed late March environmental conditions negatively impacted plant establishment and grain yields, while April and early May planting dates had higher yield, oil, and protein content. Early planting is routinely impeded in the Midwest due to cold soil temperatures and wet conditions (Andales et al., 2000; Hu & Wiatrak, 2012). Furthermore, cool soil temperatures reduce soil N mineralization due to a lack of microbial activity and a late frost can decrease yield and grain quality (Lam et al., 2001; Meyer & Badaruddin, 2001).

Yields can be reduced during late planting due to lower insolation periods taking place and triggering reproductive stages early on in soybean plant development (Egli & Bruening, 1992). Drought stress during reproductive stages brought on by June planting can decrease vegetative growth, duration of the seed filling stage, and seed size; as grain yield is generally associated with the duration of flowering and pod set stages (D.B. Egli & Bruening, 2000). Grain quality can also become an issue in delayed planting scenarios, where underdeveloped plants experience high summer temperatures and drought stress, negatively impacting protein and oil content (Hu & Wiatrak, 2012). Research suggests that soybeans can be planted in late April in Michigan, with only a 25% chance of a killing frost after May 1st in areas north of the 42nd parallel (De Bruin & Pedersen, 2008).

Nitrogen

Due to the high protein content found in soybean grain, plants have a high N requirement (Osborne & Riedell, 2006). Soybeans can access N from three potential sources: soil mineralization, biological N fixation (BNF), or synthetic N fertilizer (Salvagiotti et al., 2008).

There are two plant-available forms of nitrogen: ammonium (NH_4^+) and nitrate (NO_3^-) (Medford & Hatzell, 2017). Soil N mineralization is maximized when soil temperatures reach 25ºC, resulting in slow mineralization rates early in the growing season when temperatures are below 25ºC. (Guntiñas et al., 2012). Li et al. (2019) found soil N to be significantly increased as soil microbial biomass increased. If N content, or water to remobilize N, is not adequate for the number of seeds produced on the soybean plant, seeds will be lighter, have lower protein content, or abort altogether (Kinugasa et al., 2012). Soybean N uptake at grain fill has some practitioners questioning the most adequate timing and source of N fertilization (Mann & Below, 2017; Osborne & Riedell, 2006). On most midwestern soybean acres, N fertilizer is rarely applied other than a small amount of 'starter' fertilizer (Cafaro La Menza et al., 2017). However, nitrogen application in soybean has become more common in high-yield environments as genetics have improved yield potential beyond that which BNF may be able to supply (Mann & Below, 2017). Since the triple bond of atmospheric nitrogen (N_2) is very energy intensive to break, the future of manufactured nitrogen application may be reserved for more N-sensitive crops (Medford & Hatzell, 2017). Mann & Below, (2017) evaluated multiple N sources under various timings; pre-plant, V3, R1 and R3 growth stages on Illinois soybean yield. They found both N source and application timing highly impacted grain yield. As growth stages progressed, yield response declined to all N sources except for 28% UAN. Nodule size, number, and rate of BNF decreased as the amount of applied nitrogen increased (Gibson & Harper, 1985). Fujikake et al. (2003) found a decrease in carbohydrates supplied to nodules as nitrate levels increased, implying that excess nitrate may be partitioned to the roots instead of nodules.

Applying N to soybeans in Michigan is currently not recommended due to inconsistent yield responses (Warncke et al., 2009). However, 44% of Michigan soybean acres have N applied at some point during the growing season (Purucker & Steinke, 2020). The best time to apply N to soybeans is still somewhat uncertain, but reviewed literature suggests a late-season, early reproductive stage timing will maximize the rate of return (Bender et al., 2015; Mann & Below, 2017).

Phosphorous

Phosphorus (P) is important for root development, seed formation, stalk strength, and promotes N-fixation (Thakur et al., 2014). Soil-supplied P is typically in abundance, however, 30-60% is present as organic compounds in the lattice structure of clays and silicate minerals, leaving a smaller fraction as inorganic compounds which are sorbed to soil particles, and can be actively dissolved in soil/water solution which are plant available (Larsen, 1967). A slow rate of desorption from primary minerals is the main pathway where mineral P is transformed to dissolved P, and thus available for plant uptake (Penn et al., 2014). The mobile portion of the soil P pool may be mobile in the soil via soil organisms, moving water (mass flow) or along concentration gradients (diffusion) (Larsen, 1967). Because soil applied P moves primarily along a concentration gradient, changing the rate of fertilizer applied, and thus influencing the gradient, can manipulate P movement in the soil (Larsen, 1967).

Phosphorus fertilizer is mined from phosphate rock, a non-renewable resource (Syers et al. 2008). Phosphorus amendments can be broadcast, or band applied, typically 5/cm below and 5/cm to the side of the seed. Band-applied P fertilizer moves via diffusion and does not readily leach (Hansel et al., 2017). P fertilizer is often inefficiently absorbed, and thus linked to surface water pollution (Hill et al., 2015). Hansel et al. (2017) evaluated the placement of triple super phosphate, tillage, and water regimes in soybean and found that subsurface banding P provided greater root length, root density, and grain yield in no-till or strip-till systems (Hansel et al., 2017). Braun et al. (2020) studied desorption and isotope exchange of P in soils and observed soil test analyses such as the Olsen test were accurate predictors of the rate of desorption from both fast and slow-releasing soil P pools (Braun et al., 2020). Critical levels (CL) of soil test phosphorus for most Michigan row crops is currently 15/ppm (Warncke et al., 2009, Hankinson et al., 2015).

Potassium

Often referred to as the 'forgotten nutrient' potassium (K) provides many benefits to soybeans. Potassium is uniquely bound to negatively charged soil particles and is part of the cation exchange capacity (CEC) and is plant available as K^+. Due to its formal charge, K fertilizer management may be different compared to other macronutrients like N or P which are not bound to CEC (Warncke & Brown, 1998). Current soil-applied K recommendations in Michigan are based on a critical level dependent upon soil CEC being above or below 5 meq/100mg soil (Culman et al., 2020).

Potassium differs from N and P once inside the plant as it does not bind with carbon or oxygen, and it is not part of a protein or any other organic compounds inside the plant (Hoeft et al., 2000). Potassium is involved in enzyme activation, photosynthesis, and transportation of sugars, and is involved in metabolic pathways which increase crop quality (Tiwari et al., 2002). Plant uptake of other essential nutrients can be linked to K fertilization or availability (Dibb & Thompson, 2015). Jones et al. (1977) reported K synergism regarding the number of and fresh weight of nodules as K fertilization rates increased. However, maximum nodulation was achieved when both P and K fertilizers were applied (Jones et al., 1977). Farhad et al. (2010) studied differing rates of K fertilizer (muriate of potash) in conjunction with S (Gypsum) fertilizer on clay loam soil and found when both K and S applications were combined, a significantly higher seed yield was achieved than either nutrient alone (Farhad et al., 2010). Excess K fertilization can lead to luxury consumption by soybean plants (Warncke et al., 2009). Despite a high K regime and excessive use of K, soybeans do not accumulate much K in the grain (Sale & Campbell, 1986).

Sulfur

Sulfur (S) is an essential plant nutrient that until recently was supplied to crops in the upper Midwest through industrial emissions and less refined fertilizers (Hawkesford & De Kok, 2006; Scherer, 2001). Fertilizers contain sulfur as, sulfate, or elemental sulfur, or a combination of both. Sulfate esters are readily plant available, while 95% of elemental S will be carbon-bonded in the soil and must undergo mineralization by microbes to become plant-available (Scherer, 2001). Each form of S is necessary to capture both short-and long-term sulfur availability (Scherer, 2001). As soybean yield has increased in the US from 2562 kg ha^{-1} in the year 2000 to 3443 kg ha^{-1} in 2020, sulfur removal by the soybean crop has increased by approximately 25% (Dick et al. 2015; USDA-NASS, 2021). Soybean response to S application can vary due to soil type, weather, and crop requirements. Soils that typically become sulfur deficient are those that are coarse-textured, well-drained, low in organic matter, and prone to leaching (Dick et al., 2015). Current analyses of sulfur availability in soil are highly inaccurate, to ensure sulfur requirements are being met, a plant tissue analysis is recommended (Culman et al., 2020).

Biological N Fixation

Although 78% of the atmosphere is N_2 gas, the stability of the triple bond between nitrogen atoms is difficult to break, leaving much of the global N supply tied up in the air we breathe, however, certain prokaryotes can symbiotically harvest this nitrogen with a leguminous host (Ohyama, 2011). Biological N Fixation is ecologically beneficial as it reduces the need for synthetic nitrogen fertilizer (Chang et al., 2015). The time at which nitrogen fixation begins in soybean is variable, between VE and V6 growth stages but fluctuates depending on soil temperature, moisture, and available nutrients to developing seedlings. (Fujikake, 2003; Salvagiotti et al., 2008). Gram-negative soil rhizobia (*Rhizobiaceae*) are drawn to soybean roots selectively by secretion of iso-flavonoids from root hairs. Once in contact, the rhizobia infect the plant and cause a nitrogen-fixing symbiosis (Stacey et al., 2006). The nitrogen fixation process begins when bacteria enter the root and begin to multiply. Within the cortex cells, the plant provides the necessary nutrients and environment for the bacteria. Around 2-3 weeks after seed germination, new bacterial infections create small nodules which are visible to the naked eye (Purcell et al., 2004). Nodules begin producing nitrogen once they turn pink or red, as they produce leg-hemoglobin that controls bacterial oxygen uptake (Flynn & Idowu, 2015).

Soybean yield is directly correlated to N uptake by plants, 44-72% of which is typically supplied by BNF (Ciampitti & Salvagiotti, 2018). Field studies from 1966-2006 show that maximum N fixation occurs as pods form (R3 growth stage), and the maximum percentage of N derived from the atmosphere occurs at full pod formation (R4 growth stage) (Bender et al., 2015; Brar & Lawley, 2020; Ciampitti et al., 2021; Salvagiotti et al., 2008). Salvagiotti et al. (2008) estimated the average BNF contribution was 111-125kg N ha^{-1}. Fujikake et al. (2003) observed soybean plants in nitrate-rich environments decrease the supply of carbohydrates to nodules and can inhibit, delay, or reduce N contributions. Contrarily, if inorganic N is unavailable, plant requirements can be primarily met by fixation (Purcell et al., 2004). When synthetic N fertilizer is applied and soil-supplied N is no longer limiting, fixation via BNF can be reduced by 44% in field settings (Santachiara et al., 2019).

N^{15} Analysis

Plant analysis for nitrogen derived from the atmosphere (%NDFA) has been done with several methods, including acetylene reduction, measuring ureide concentration, and N^{15} enrichment dilution. The N^{15} enrichment method is the most accurate analysis of but also the most expensive (Purcell et al., 2004). The enrichment method utilizes a soil-applied fertilizer such as ammonium nitrate with 99 atomic% N^{15} ($^{15}NH_4{}^{15}NO_3$) and a non-nodulating or grass comparison species. An analysis is performed against the known volume of N^{15} applied. The enrichment method relies on available forms of N for plant uptake, such as actively mineralized soil N, fertilizer-supplied N, and atmospheric N_2 supplied by nodulation (Boddey et al., 1995; Ciampitti et al., 2021). A less expensive method, the natural abundance method, (Amarger et al., 1979 and Kohl et al., 1980) utilizes the 0.365% atmospheric abundance of N^{15} as a traceable volume of % NFDA between nodulating and non-nodulating or grass species. (Chalk et al., 2016; Ciampitti et al., 2021). Chalk et al. (2016) compared the enrichment and natural abundance methodologies and found they provide different results under the same conditions, which suggests each method should be based on its own scale (Chalk et al., 2016). The equation for evaluating the natural abundance and dilution methods, developed by Unkovich et al. (2008) is as follows: Natural abundance NDFA(%) = (((δ^{15}N of reference plant – δ^{15}N of soybeans) / (δ^{15}N of reference plant – Bvalue)) * 100) (abundance method B-value refers to the δ^{15}N value for soybean grown with atmospheric N only) Dilution method NDFA (%) = (((δ^{15}N of soybean – δ^{15}N of atmosphere) / (δ^{15}N soil inorganic pool – δ^{15}N of atmosphere)) * 100) (where atmospheric ^{15}N content is 0.3663%).

Soybean Lag Phase

Once a soybean seedling has emerged there is a brief period where vegetative production and nutrient accumulation are reduced, known as the "lag phase" (LP) of nutrient accumulation. During this time, plants do not yet have enough structure to adequately uptake soil-derived nutrients (Bender et al., 2015). Shortening the duration of the lag phase may be one method to increase soybean grain yield. Duration of the LP is influenced by environmental conditions after planting (DeLuca et al., 1992). One-way growers may be able to shorten this period is by using starter fertilizer applied at planting to increase nutrient availability to seedlings (Bender et al., 2015; Hankinson et al., 2015; Purucker & Steinke, 2020). Bender et al. (2015) studied nutrient uptake of three soybean cultivars across fertility practices and found that a starter fertilizer application resulted in greater dry matter (DM) accumulation 45 days after planting (DAP), and greater DM at physiological maturity (R8 growth stage) compared to a control. Typically occurring between VE and 45 DAP, the LP is still measurable in TDM production at physiological maturity between treatments receiving starter fertilizers and those without (Bender et al., 2015). Dry matter production at V4 was influenced by 12-40-0-10s starter fertilizer, but a lack of response to MOP may indicate K is adequately supplied by soil until this time in the growing season (Purucker & Steinke, 2020).

Irrigation

An estimated 10% of the 35.45 million hectares of soybeans grown in the U.S. in 2018 were under irrigation (NASS, 2018). In Michigan, 77,882 hectares of mostly sandy loam, or loamy sand were irrigated in the same season (NASS, 2018). Few acres of loam soils in Michigan are irrigated because of the greater water-holding capacity of loam and clay soils

(Goldy, 2012). Water deficit is the largest yield-limiting factor in most Midwest soybean-growing regions which is becoming more frequent due to climate variability (Gava et al., 2018).

Field capacity (FC) is a term that refers to a soil's ability to hold water against gravity. A field capacity of 100% is completely saturated and 0% is the permanent wilting point of crops (Colman, 1947). Irrigation is traditionally triggered when FC reaches 35% to 45% depletion (Torrion et al., 2014). Recent research has been focused on determining when to irrigate based on the water-stress sensitivity of a crop during peak periods of development (Heatherly & Elmore, 2004; Van Doren & Reicosky, 1987). In Michigan, the average rainfall in July and August is 8.66 and 8.02 centimeters respectively, while soybeans require between 50-66 centimeters of water during a growing season, 65% is utilized between R1 and R6 (i.e., July and August) (Kranz & Specht, 2012; US Department of Commerce, 2021). Soybean water demand is greatest in August during pod-set and seed-filling stages, (beginning at the R3 growth stage) and irrigation is not recommended until then (Klocke et al., 1989; Torrion et al., 2014). Beginning irrigation too early in the growing season can promote plant lodging due to the lengthening of internodes in the upper portion of the stem, resulting in taller plants that are vulnerable to falling over in late-season thunderstorms (Kranz & Specht, 2012).

Garcia et al (2010) compared different cultivars across irrigation strategies beginning at different times in the growing season and found that there were significant differences between water regimes on TDM and seed yield. Torrion et al. (2014) found despite early season FC levels well below 35% depletion, the deferment of irrigation until R3 outperformed both the season-long control and rainfed control. Drought stress during soybean reproductive stages can also reduce grain yield and qualities such as oil, protein, fiber, and linolenic acid content (Assefa et al., 2018). Ultimately, irrigation should be based on maintaining field capacity to protect achievable yield goals during peak times of evapotranspiration (Zhang et al., 2014).

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CHAPTER 2: SOYBEAN BIOLOGICAL NITROGEN FIXATION AND PRODUCTION AS AFFECTED BY STARTER FERTILIZER, NITROGEN APPLICATION, AND PLANTING DATE

Abstract

Michigan spring weather variability combined with earlier planting dates may provide opportunities for starter fertilizer to affect soybean (*Glycine max* L. Merr.) early season dry matter production while simultaneously decreasing the time interval for nutrient accumulation (i.e., lag-phase). However, potential nitrogen (N) fertilizer impacts on inhibition of biological N fixation (BNF) are not well known, especially in high-yield environments (i.e., irrigation). Two multi-year field studies were established on irrigated and non-irrigated sites to examine two planting dates representative of early and conventional timings (23 April and 17 May in 2021, 29 April and 20, May in 2022) and six fertilizer strategies including non-treated control (NTC), two starter fertilizers (liquid and granular) containing 28 kg N, 67 kg P_2O_5, and 17 kg S ha^{-1} applied 5 cm to the side and 5 cm below the seed (5x5) at planting and three N timings (pre-pant incorporated, V4, and R2) of 112 kg N ha^{-1}. Starter fertilizers containing < 28 kg N ha^{-1} did not adversely affect late-season (R6) BNF measurements while all N timings receiving > 112 kg N ha^{-1} negatively impacted both percentage of N derived from the atmosphere (NDFA) and relative abundance of ureides (RAU). In one of four site years, April planting increased yield as compared to May. Starter fertilizer did not improve yield beyond NTC during April or May planting in any site year. In the current environments tested 5x5 starter and N fertilizers may accelerate plant growth but none are substitutions for BNF. Contrasts assessing grain yield of N fertilizer treatments in comparison to NTC were insignificant across both sites and years

suggesting maximum yields were attainable through BNF contributions and current soybean cultivars did not require supplemental N fertilizer under the conditions of this study.

Introduction

Increased spring weather variability including abnormally wet or dry soil moisture conditions have increased interest in utilizing nutrient management strategies that may support early-season soybean (*Glycine max* L.) dry matter production and nutrient accumulation but not adversely affect biological N fixation (BNF) contributions to the plant. As demand for both yield and greater soybean quality (i.e., oil and protein) increases, nutrient management strategies may become critical to mediate the effects of climate variability, diminish the environmental impacts of agricultural inputs, and improve grower economic return (Goldsmith, 2008). Earlier planting dates may offer additional opportunities for Michigan soybean growers to capitalize on a longer nutrient uptake period prior to reproductive stages allowing for greater early-season dry matter (DM) accumulation and capability to produce more mainstem nodes (Egli & Cornelius, 2009). Previous research indicated little response to in-season nitrogen (N) application, however, environments supporting yields > 4500 kg ha^{-1}, such as those under irrigation, may have appropriate conditions to produce a yield response (Wesley et al., 1998; Barker & Sawyer, 2005). Irrigated environments may alter soybean nutrient uptake and yield response and require management strategies that may not function well under non-irrigated conditions.

As mean farm size increases, greater interest in earlier soybean planting offers opportunities to influence DM production, grain yield, and oil content (Robinson et al., 2009). Due to a northerly climate and proximity between the Great Lakes, Michigan spring soil conditions are less predictable offering greater potential to utilize starter fertilizer. Cool, cloudy conditions often limit soil temperatures to < 10ºC inhibiting spring soil N mineralization and microbial activity which can impact early season biological nitrogen fixation (BNF) (Lam et al., 2001; Pettersson et al., 2005) Late March environmental conditions often inhibit plant establishment while April to early-May maximize grain yield and quality (Robinson et al., 2009). Hankinson et al. (2015) found a 39.0 kg ha^{-1} d^{-1} decrease in grain yield for every delayed planting day after 1 May through early July. Previous research indicated greater DM helped facilitate nutrient uptake as pre-R5 DM was associated with greater yield (Purucker & Steinke, 2020).

Starter fertilizer may shorten the ‘lag phase’ of early-season soybean growth by providing seedlings with additional nutrients during periods of reduced soil mineralization and microbial activity (Bender et al., 2015; Hankinson et al., 2015; Purucker & Steinke, 2020). Bender et al. (2015) described the lag phase of nutrient accumulation to take place between VE and 45 days after planting (DAP). Confounding results to starter fertilizer are likely due to the influence of environmental conditions after planting (DeLuca et al., 1992). In Michigan, starter fertilizer is typically band applied and placed 5 cm below and 5 cm to the side of the seed row (i.e., 5x5). Band placement allows for nutrient diffusion away from a concentrated source while placing fertilizer in close proximity to the seed, yet distant enough away to avoid salt damage to developing roots (Rutan & Steinke, 2018). In several studies, low rates of starter N fertilizer ($<$ 28 kg ha^{-1}) were found to support increased V4 DM, but yield and profitability were inconsistent, and effects on BNF unknown (Osborne & Riedell, 2006; Purucker & Steinke, 2020). Hankinson et al. (2015) evaluated five starter fertilizers containing N, P, or both, applied as 5x5 placement, and found starter fertilizer had limited effects on soybean nodulation, DM accumulation, canopy closure, grain quality, and no effect on grain yield. Although low starter N rates have not decreased BNF, more data are needed regarding the influence of greater N rates on not only total dry matter (TDM) and grain yield but also BNF contributions to the plant (Salvagiotti et al., 2008).

Close to 70% of total phosphorus (P) uptake in soybean occurs after R1, of which half will originate from the soil mineralization (Bender et al., 2015). Although Michigan soils typically have an abundance of P, 30-60% is present as organic compounds in the lattice structure of clays and silicate minerals, this leaves a small inorganic fraction sorbed to soil particles that may be actively dissolved in soil/water solution becoming plant available (Larsen, 1967). Phosphorus fertilizer moves via diffusion, often leaving a granule within days after application and sorbing to other minerals within weeks (Fixen & Bruulsema, 2014). Placing P in a 5x5 band artificially creates a concentration gradient that can promote root development and soybean N-fixation (Thakur et al., 2014; Hansel et al., 2017). Rosa et al. (2020) evaluated P placement on soybeans and found band application increased V3 tissue P accumulation 30% compared to a non-treated control, while broadcast application maximized R3 P accumulation, however, neither strategy affected yield. Early-season soybean response to P often does not result in greater yield unless soil test P levels are low (< 20 mg/kg Mehlich-3) indicating a greater likelihood of response to fertilization (Culman et al., 2020).

While many starter fertilizer programs focus on primary nutrients, some cropping systems have become responsive to sulfur (S) (Camberato et al., 2022). Increased fertilizer purity and concentration along with a lack of industrial atmospheric deposition have increased S deficiencies over the last two decades (Scherer, 2001; Hawkesford & De Kok, 2006; Camberato et al., 2022). Purucker & Steinke (2020) found starter S accounted for < 10% of total soybean S uptake at V4, suggesting that S did not influence V4 DM production. However, S is a co-factor for nodulation and early-season deficiencies may impact BNF contributions later in the season

(Camberato et al., 2022). Mahal et al. (2022) applied multiple sources of elemental and sulfate-based fertilizers across ten site years and observed no soybean grain yield response. The inability of soil tests to sufficiently extract S (mono-calcium phosphate extraction) leaves few tools for determining the likelihood of crop response to S application (Franzen, 2018; Culman et al., 2020; Camberato et al., 2022). Soil-applied S may offer the best response on low organic matter soils (i.e., < 20 g kg^{-1}) with minimal S application history and where minimal carbon inputs (e.g., manure, cover crops) are utilized (Purucker & Steinke, 2020, Crespo et al., 2021).

Due to high grain protein concentration, soybeans have a large N requirement and can remove as much as 8.3 kg N per 100 kg soybean grain often exceeding the corn (*Zea mays*, L.) N removal rates (Osborne & Riedell, 2006; Warncke et al., 2009; Bender et al., 2015). If R3 plant N concentrations (or water to remobilize N) are not sufficient for the number of seeds produced on the soybean plant, seeds will become lighter, decrease protein content, or possibly abort (Kinugasa et al., 2012). Soybean N uptake is often split 50/50 before and after the R4 (i.e., seed-fill) growth stage (Bender et al., 2015). Biological N fixation can provide 44-72% of the soybean N requirement with the remainder coming from soil N mineralization and root uptake (Ciampitti & Salvagiotti, 2018).

Nodulation may begin anytime between VE to V6 but can be reduced or delayed by environmental conditions and soil properties including water stress, cool soil temperatures, high soil N content, or sub-optimal soil pH (Graham, 1992; Bordeleau & Prévost, 1994; Fujikake, 2003; Salvagiotti et al., 2008; Coskan & Dogan, 2011). The soil-borne rhizobia (*Bradyrhizobium japonicum* L.), responsible for nodule production, are free-living symbiotic N-fixing organisms that require carbon from leguminous roots for survival (Drevon & Salsac, 1984). To fix N_2 from the atmosphere and transform into NH_4 the nitrogenase enzyme requires an anaerobic environment which is found within the root nodule where rhizobia are contained (Rutten et al., 2021). Leg-hemoglobin (i.e., vitamin B12) facilitates the creation of this low O_2 environment and also gives nodules their pinkish internal color (Yadav & Khanna, 1988). Andrews et al., (2009) quantified energy requirements for N fixation and found N_2 via BNF cost 5-7% more ATP than the assimilation of NH_4^+ or NO_3^- from soil solution. Previous studies indicated maximum N fixation occurred at beginning pod formation (R3), while the maximum percentage of N derived from the atmosphere (NDFA) occurred at full pod formation (R4) (Bender et al., 2015; Brar & Lawley, 2020; Ciampitti et al., 2021). Almeida et al, 2023 evaluated 26 locations across 12 midwestern states to quanitify the degree of soybean response to N-S fertilization and found a range of N-fixation contributions from 2-89% across sites and N strategies. Mid-reproductive-stage N demands have practitioners questioning the timing and rate of N application (Osborne & Riedell, 2006; Mann & Below, 2017). In 2018, 50% of Michigan soybean acres were fertilized with N, a 6% increase from 2012 (USDA-ERS, 2019). Zuffo et al. (2018) evaluated four N rates at three timings (at-plant, 30 DAE, and 50 DAE) finding no effects on BNF qualities, grain yield, or harvest index regardless of rate or timing. In high-yielding environments (i.e., irrigation) a yield response to N application may be more probable as soil-derived N and BNF may not adequately supply peak N uptake demands (Wesley et al., 1998; Salvagiotti, 2009). However, a better understanding of the gap between fixed N_2 and total N uptake may better determine whether or not there is a need for N fertilizer (Santachiara et al., 2019).

As of 2018, an estimated 10% of total soybean hectares were irrigated (NASS, 2018). In Michigan, approximately 77,000 soybean hectares consisting of mostly sandy loam or loamy sand soils are irrigated with the greater water-holding capacity of heavier-textured soils not requiring supplemental water (Goldy, 2012; NASS, 2018). Although Kranz & Specht (2012) found 65% of soybean water use occurred between R1 and R6, Michigan soybean production may especially require supplemental water in late July and early August when summer precipitation may be in a deficit (NOAA, 2022). Irrigation is not recommended until R3 as irrigating too early in the growing season can lengthen upper stem internodes resulting in taller plants more vulnerable to lodging later in the season (Klocke et al., 1989; Kranz & Specht, 2012; Torrion et al., 2014). The current study evaluated differences in plant morphology and biological N fixation to better understand how management may differ between a non-irrigated and irrigated (i.e., high-yielding) environment, thus soil moisture was maintained at field capacity for irrigated site years.

The objective of this study was to evaluate the impacts of planting date, liquid vs granular 5x5 starter fertilizer, and three individual N application timings on BNF (i.e., nodule count, N^{15}, relative abundance of ureides), DM accumulation, grain yield, and grower profitability across irrigated and non-irrigated environments. Pre-planned orthogonal contrasts were chosen prior to initiating field studies to specifically compare the influence of granular vs. liquid 5x5 starter fertilizer and PPI vs. V4 vs. R2 N application strategies, amongst other combinations of planting date by fertilizer strategy.

Materials and Methods

Field trials were conducted in Lansing, MI (42º41’20.8” N 84º29’10.8” W) during 2021 and 2022 on irrigated and non-irrigated Conover loam soil (fine-loamy, mixed, active, mesic Aquic Glossudalf). All sites were previously cropped to corn followed by autumn chisel plowing (20 cm depth) and spring field cultivation (10 cm depth). Pre-plant soil samples (20 cm depth) were taken prior to nutrient application, ground to pass through a 2-mm sieve, and analyzed for soil chemical properties (Table 2.01). Weed control consisted of early post-emergence application of glyphosate (N-(phosphonomethyl) glycine) followed by a second pass of acetochlor (2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide) and glyphosate. Fungicide was applied at irrigated locations as a grower standard practice using boscalid (3-pridinecarboxamide, 2-chloro-N-(4’-chloro(1,1’-biphenyl)-2-yl) at the R1 growth stage. Irrigated locations were supplied with 12.7 and 20 cm of supplemental water during the 2021 and 2022 growing seasons, respectively, from a Micro Rain (model MR58RLBP) traveling irrigator (Micro Rain, Yukon, OK). Irrigation strategy consisted of maintaining field capacity (FC) during peak evapotranspiration and low soil moisture conditions in order to promote a high-yield environment (i.e., > 4500 kg ha^{-1}). Environmental data obtained from Michigan State University Enviro-weather (https://mawn.geo.msu.edu/). Temperature and 30-yr means were obtained from the National Oceanic and Atmosphere Administration (NOAA, 2022).

Trials were arranged as a randomized complete-block split-plot design with four replications. Main plots consisted of planting dates: 23 April and 17 May in 2021 and 29 April and 20 May in 2022. Sub-plots consisted of six fertilizer treatments: i) nontreated control (NTC), ii) 168 kg MicroEssentials® S10® (Mosaic CO., Plymouth, MN) combined with 14.5 kg urea ha^{-1} applied 5x5 to provide 28, 67, and 17 kg N, P, and S ha^{-1}, respectively (Granular 5x5), iii) 48.6 L ammonium thiosulfate combined with 142.2 L ammonium polyphosphate ha^{-1} applied 5x5 to provide 28, 67, and 17 kg N, P, and S ha^{-1}, respectively (Liquid 5x5), iv) 243 kg urea ha^{-1} applied PPI to provide 112 kg N ha^{-1} (PPI N), v) 311 L urea ammonium nitrate ha^{-1} band applied at growth stage V4 to provide 112 kg N ha^{-1} (V4 N), and vi) 311 L urea ammonium nitrate ha^{-1} band applied at growth stage R2 to provide 112 kg N ha^{-1} (R2 N). Plots measured 4.6 m in width and 12.2 m in length with row spacing at 76 cm planted with a Monosem planter (Monosem Inc., Kansas City, KS) using variety P24T35E (Pioneer Co., Johnston, IA). In-season fertilizer applications were made using a backpack sprayer equipped with orifice body nozzles and short drop hoses to place fertilizer 5-10 cm from soybean stems.

Plant stand counts occurred 20-30 days after emergence to assess planting date and starter fertilizer impacts on population. Fractional green canopy coverage (FGCC) was taken every 10-14 days until full canopy. Normalized Difference Vegetation Index (NDVI) was recorded at V4, R1, and R5 to detect differences in canopy color among treatments. Above-ground biomass samples were collected at V4, R2, R6, and R8, when approximately 50% of plants achieved the respective growth stage (Fehr & Caviness, 1977). Biomass samples consisted of 5 consecutive plants from the second row of each plot. Prior to leaf senescence, 1 cm by 1 cm square netting was constructed around the sample area to retain biomass. Plants were dried at 60ºC (0% moisture) and weighed for total dry matter production. At growth stages R2 and R6, samples were taken to measure relative abundance of ureides (RAU) and N^{15} concentration (Ciampitti & Salvagiotti, 2018). A length of 152 cm was harvested from the second row of each plot to determine dry matter accumulation, number of plants, and fresh weight. A sub-sample of five whole plants was then collected for N^{15} analysis and an additional five whole plants for RAU analysis. Sub-samples were weighed fresh, dried (0% moisture), and ground to pass through a 1 mm mesh screen for analysis. Non-fertilized corn located in the same field was utilized as a non-leguminous reference crop for biological N fixation (BNF) estimations. Nodule counts from five plants were recorded at R4 by harvesting all below-ground root biomass of five consecutive plants from the second row and counting the total number of nodules. A Kincaid 8XP (Kincaid Equipment Manufacturing, Haven, KS) research plot combine harvested rows 4 and 5 of each plot on 18 October 2021 and 05 October 2022 for grain yield, moisture, and test weight, with yield adjusted to 135 g kg^{-1} moisture.

A partial budget was used to calculate net economic return by subtracting fertilizer input costs from gross revenue (i.e., grain price multiplied by yield). Input costs included fertilizer and application costs obtained from local retail grain elevators and Michigan State University Extension Custom Machine and Work Rate Estimates (Stein, 2021). Application costs were US$7.36, $15.27, and $27.92 ha^{-1} for subsurface 5x5 nutrient application, PPI broadcast application and incorporation, and surface banding, respectively. Fertilizer input costs in 2021 were US$152.83, $184.79, $159.53, and $173.25 ha^{-1} while costs in 2022 were US$258.47, $290.87, $308.81, and $323.98 ha^{-1} for dry 5x5, liquid 5x5, PPI N, and V4/R2 N, respectively. Economic return estimates were derived by subtracting fertilizer and application costs from a local cash price of $0.40 and $0.44 kg^{-1} in 2021 and 2022, respectively.

Data were analyzed separately by site year due to irrigation or no irrigation and significant treatment-by-year interactions and subjected to analysis of variance using the GLIMMIX procedure in SAS (SAS Institute Inc., 2017). Replication was considered a random factor while planting date and fertilizer were considered fixed factors. The normality of residuals was tested with the UNIVARIATE procedure ($P \leq 0.05$). Levene's Test of squared and absolute values of residuals was examined to confirm homogeneity of variances ($P \leq 0.05$). Least square means were separated using the LINES option of the slice statement when ANOVA indicated a significant interaction ($P \leq 0.10$).

Results

Environmental Conditions

Growing season (May-Sept.) precipitation was +18% and -32% from the 30-yr mean in 2021 and 2022, respectively (Table 2.02). However, cumulative April and May precipitation was down 68% and 22% from the 30-yr mean in 2021 and 2022, respectively, creating dry early-season moisture conditions. The 12-day period from 18 June to 30 June 2021 delivered > 16 cm precipitation creating normal (i.e., within 10% of 30-yr. mean) moisture conditions despite earlier season drought. Two-to-three-week dry periods during July-Sept. created drought conditions during critical stages of soybean development likely impacting yield potential. June, July, and September 2022 precipitation was 56%, 40%, and 20% below the 30-yr mean creating a growing season moisture deficit. Mean monthly air temperatures across years were within 1.5 ºC of the 30-yr average (Table 2.02). Soil temperatures (5 cm) did not persist above 10ºC until 30 May 2021 and 24 May 2022 likely decelerating early-season seedling development.

Grain Yield and Quality

Irrigated Conditions

No planting date and fertilizer strategy interactions on grain yield occurred in either site year (Table 2.03). Grain yield ranged from 5111-5535 kg ha^{-1} and 4311-4896 kg ha^{-1} in 2021 (i.e., 21-I) and 2022 (i.e., 22-I), respectively (Table 2.04). April planting (i.e., 24 days before the May planting date) significantly increased grain yield 8% (424 kg ha^{-1}) in 2021 but no main effects occurred in 2022. Reductions in April planted 2022 V3 stand counts (i.e., <158,000 plants ha^{-1}) due to late-season frost resulted in a 17% stand reduction at harvest as compared to May planting thus likely limiting yield potential of early-planted soybean (data not shown). Fertilizer strategy only influenced grain yield in 2022 with yields ranging from 4896- 4311 kg ha^{-1} (Table 2.04). Granular 5x5 starter, PPI, V4, and R2 N treatments all produced similar yields. However, the NTC and liquid 5x5 starter were both significantly less than PPI N. Inconsistent 2022 grain yield was accompanied by reduced test weights (i.e., <63.4 kg hL^{-1}). April planting produced 1.2% and 1.3% significantly greater grain oil content in 2021 and 2022, respectively, but early planting significantly decreased protein concentration 1.3% in 2022 (data not shown).

Non-irrigated Conditions

Grain yield was not significantly impacted by planting date or fertilizer strategy during either site year (Table 2.03). May planting 2021 (i.e., 21-NI) significantly improved grain protein content 0.7% compared to April but no differences in 2022 (i.e., 22-NI) (Table 2.04). Grain protein content in 2021 was reduced 0.5-1.3% where PPI N was applied compared to the NTC. Nitrogen treatments at V4 and R2 significantly reduced grain protein content as compared to granular 5x5 starter fertilizer (data not shown). Results were similar for fertilizer treatment in 2022, however, NTC did not remain similar to liquid 5x5 starter fertilizer. Increased grain protein often results in decreased oil concentrations. Planting date and fertilizer strategy interacted to affect 2021 grain oil content resulting in greatest oil concentration from R2 N of April planting, and PPI N from May planting (data not shown). However, while the interaction is statistically significant, differences between fertilizer treatments within planting dates only ranged between 22.6-23.2% for April and 22.1-22.7% for May-planted soybeans. No interactions nor planting date differences occurred in 2022 regarding oil concentration. Fertilizer treatment affected 2022 grain oil concentration, but, differences were < 0.5% of the overall concentration. The minor protein and grain oil differences from fertilizer application likely demonstrate little value under the rates and conditions of the current study.

Biological N Fixation

Irrigated Conditions

In 2021, mean nodule counts taken at R4 were significantly greater under April planting versus May, but no differences occurred in 2022 (Table 2.05). Fertilizer strategy did not influence nodule production during either site year. There were no interactions between planting date and fertilizer strategy nor main effects of planting date on R2 or R6 N^{15} content (NDFA) or relative abundance of ureides (RAU) in 2021 or 2022 (Table 2.06, Table 2.07). Compared to no fertilizer application, the R2 RAU declined 17.7 – 19.3% from V4 N applications across both study years while R6 RAU declined 1.1-3.3% and 2.6-3.4% from V4 and R2 applications in 2021 and 2022, respectively. Both 2021 PPI and V4 N applications reduced R2 NDFA by 11.9 – 14.8% compared to NTC (Table 2.06). In 2022, only PPI N reduced R2 NDFA (-18.3%) while PPI, V4, and R2 N all reduced R6 NDFA 1.2-3.4% (Table 2.07). The R6 NDFA and RAU values from both liquid and granular 5x5 starter fertilizers were similar to the NTC in 2021 and 2022. Results sharing similarities with NTC suggest starter fertilizer, regardless of liquid or granular composition, and containing up to 28 kg N ha^{-1} did not negatively affect NDFA during peak N fixation (i.e., post R4 reproductive growth stages).

Non-irrigated Conditions

Main effects of planting date and fertilizer strategy impacted nodule production in 2021 but not in 2022 (Table2.05). April-planted soybean produced on average 32 more nodules per plant than May planting, while PPI N was the only fertilizer treatment to reduce nodulation (Table 2.05). Planting date and fertilizer strategy interacted to affect 2021 R2 NDFA and R2 RAU (Table 2.08, Table 2.09). April planted PPI and V4 N treatments reduced NDFA by 14.8 and 13.2%, respectively from NTC (Table 2.06). May planted PPI N reduced NDFA by 23.4%

compared to NTC and accumulated 15% less NDFA than April planted PPI N (Table 2.08). Liquid 5x5 and NTC both resulted in the greatest R2 RAU (i.e., 79%) with sequential reductions of 9, 17, and 28% with the granular 5x5, PPI N, and R2 N treatments, respectively (Table 2.06). Starter fertilizer did not influence the May planted R2 RAU, but substantial reductions >25% occurred with both the PPI and V4 N applications (Table 2.09). May planting significantly reduced 2021 R6 RAU by 1.5% and 2022 R6 NDFA by 8.5% (Table 2.06, Table 2.07). PPI N and V4 N reduced R6 NDFA percentage by 21-29% and 13-20% in 2021 and 2022, respectively. No planting date by fertilizer strategy interactions occurred in 2022 regarding NDFA or RAU. Planting date did not affect NDFA or RAU at R2. At R6, NDFA of April planted soybean had continued to increase while May did not, resulting in an 8.5% overall difference between planting dates (Table 2.07).

Fertilizer strategy produced significant results for 2022 NDFA and RAU at R2 and R6 (Table 2.07). At both sample timings, N application at PPI, V4, or R2 all reduced RAU from levels obtained by both liquid and granular starter fertilizer, and NTC. At R6, NDFA levels of PPI and V4 N applications decreased from R2 suggesting N-uptake from applied N was diluting the amount of atmospherically derived N. Both liquid and granular 5x5 starter fertilizers as well as R2 N and NTC similarly generated the greatest NDFA values ranging from 50.6-54.7%. Orthogonal contrasts assessing the addition of starter fertilizer show R6 NDFA increased 6.7% from NTC in 2021 (Table 2.10). In 2022 the addition of starter fertilizer April-planted soybeans increased R6 NDFA 9.5% compared to May planted. Nitrogen application at V4 significantly reduced R6 NDFA 16% from liquid 5x5 starter fertilizer while PPI N was on average 20.7% lower NDFA than all treatments besides V4 N. Starter fertilizer did not reduce the number of nodules per plant at R4, RAU, or NDFA at R2 or R6 during either site year, suggesting no negative impacts on BNF when using 28 kg N ha^{-1} in a 5x5 at planting.

Soil Inorganic Nitrogen

Soil nitrate concentrations measured at R6 across fertilizer treatments from the 0-20 cm soil depth ranged from 5.8-10.4 and 3.3-4.6 mg kg^{-1} at irrigated locations and 5.6-9.8 and 5.9-14.4 mg kg^{-1} at non-irrigated locations in 2021 and 2022, respectively (data not shown). Fertilizer strategy did not significantly influence soil nitrate values in any site year except the non-irrigated location in 2022 where the V4 N application had 144% greater soil nitrate than NTC. Soil ammonium concentrations also measured at R6 were not significantly influenced by fertilizer strategy at either site during 2021 or 2022.

Dry Matter Accumulation

Irrigated

Earlier-planted soybean increased V4 DM and R8 TDM production 38% (109 kg ha^{-1}) and 27.7% (2745 kg ha^{-1}), respectively in 2021 but had no effect in 2022. In 2021, granular 5x5 increased V4 DM 43% from NTC, with both liquid and granular starter fertilizers producing 49% and 48% greater TDM than the NTC at R2. However by R6, fertilizer strategy was insignificant (data not shown). Neither planting date nor fertilizer strategy influenced TDM in 2022. Orthogonal contrasts show adding 5x5 starter fertilizer increased V4 DM 23% in 2021 but was not significant in 2022 (Table 2.10, Table 2.11) while N-fertilizer application did not increase dry matter production beyond UTC at V4, R2 R6, or R8 during either site year.

Non-irrigated

As compared to May-planting, April increased V4 DM by 33 and 125% in 2021 and 2022, respectively. May planting increased R2 DM across both site years but by R6 main effects were not significantly different in 2021 and 31% greater for April planting in 2022. By R8, April-planted TDM surpassed May-planted by 32% (2748 kg ha^{-1}) in 2021 but was not significantly different in 2022. The addition of either starter fertilizer in 2021 increased V4 DM 49-57% above the NTC, which carried through the R2 growth stage but dissipated thereafter due to accelerated soybean growth rates post-R2. Although 2021 R8 DM was not influenced by fertilizer strategy, 2022 R8 DM increased 31%, 28% and 29% above the NTC for granular 5x5, liquid 5x5, and V4 N strategies, respectively (data not shown). Orthogonal contrasts show 5x5 starter fertilizer increased V4 DM 54% and 37% compared to the NTC in 2021 and 2022, respectively (Table 2.10, Table 2.11). Dry matter increases from starter fertilizer continued through R2 (+37%) in 2021 and R6 (+24%) in 2022. Contrasts comparing the addition of N fertilizer at any time (PPI, V4, and R2 averaged) as compared to NTC did not increase DM production at V4, R2, R6, or R8 during either site year.

Economic Analysis

No net profitability interactions occurred between planting date and fertilizer strategy. April planting increased net profitability 6% (US$126 ha^{-1}) at the 2021 irrigated location with no effects across remaining site years (Table 2.12). Fertilizer strategy influenced net profitability across all four site years, but no individual treatments improved net profitability from the NTC suggesting an inability to recover treatment costs (Table 2.13). Increased 2022 fertilizer prices impacted net profitability across site years which may change as market volatility diminishes.

Discussion

This study evaluated the effects of starter N-P-S fertilizer combinations and multiple timings of N application across two planting dates in both irrigated and non-irrigated environments. Irrigated and non-irrigated environments were not intended to serve as a comparison of one another but rather fundamentally demonstrate how water management may require adjustments based on soil characteristics, symbiotic root associations (BNF), precipitation, and other environmental factors. Pre-planned orthogonal contrasts were designed to assess groups of treatments such as ‘starter fertilizer’ (i.e., liquid and granular 5x5 combined), ‘N application’ (i.e., all three N strategies combined), or any combination against the NTC of April or May planting dates. Pre-determined contrasts allowed for the comparisons between similar treatments (i.e., starter fertilizer or N treatment) to be made without consideration of non-similar treatments thus reducing the risk of type II error.

Grain Yield and Quality

Contrasts assessing grain yield and profitability from the application of starter fertilizer comparing April and May planting dates (i.e., both 5x5 starter April planted as compared to both 5x5 starter May planted) were only significant at the 2021 irrigated site (Table 2.10). No significant grain yield increases due to planting dates were observed across site years. Similarly, contrasts assessing the response of any N application during April or May planting (i.e., all three N applications April planted compared to all three N applications May planted) were also only significantly affected at the 21-I location. V3 stand counts from April planting across sites except for the 21-I location suggest maintaining adequate plant population early in the season was necessary for an adequate response to fertilizer application. Differences in plant population at the 21-I location are likely attributed to <5mm precipitation for 17 days prior to and <5mm precipitation 10 days following May planting which warranted irrigation for adequate germination and therefore affected starter fertilizer and PPI N applications in this site year alone. Previous research indicates benefits to grain yield and quality during earlier planting dates, but restricted plant establishment due to environmental conditions are known limitations (Andales et al., 2000; Robinson et al., 2009; Hu & Wiatrak, 2012). Increased seeding rates for earlier planted soybean may better combat cool, early-season conditions rather than fertilizer application. Cox et al. (2010) found that reduced plant stands may compensate by increasing the number of nodes and length of branches further generating more pods per plant. Increased branch length and node number were observed at the irrigated 2022 location where the lower branch growth filled available space between soybean plants. However due to supplemental irrigation, late-season dense vegetative cover reduced sunlight penetration into the lower canopy preventing proper development of seed-bearing pods on the elongated lower branches resulting in reduced test weights (i.e., 292-325 g 0.5 L^{-1}) and overall grain yield (Table 2.04).

Nitrogen application applied PPI increased 2022 grain yield beyond the NTC, suggesting N was either sufficiently utilized by soybean plants or subject to environmental losses due to early season precipitation coupled with mid-late season supplemental irrigation (Table 2.04). These conditions allowed BNF contributions to increase by R6 and positively influence grain yield (Table 2.07). Insignificant differences between liquid and granular starter fertilizers during all site years suggest the sulfur component of the granular fertilizer (50% elemental S and 50% sulfate) and liquid fertilizer (applied as thiosulfate and later oxidizing into sulfate) were negligibly different. While elemental S application can take multiple years for full utilization based on fertilizer form and soil type (Degryse et al., 2016), early-season cool soil conditions may have delayed utilization of sulfate S in the granular starter and did not provide any advantage when compared to the liquid starter which requires additional time, precipitation, and warm soil temperatures to oxidize. In a greenhouse study, Goos & Johnson (2001) studied tetrathionate oxidation finding at 5ºC oxidation slowed requiring 4-12 weeks to become sulfate while a 15ºC soil temperature required only 2-3 weeks. Soil temperatures did not remain above

10ºC at the 21-NI location until 30 May, suggesting the oxidation process may have been impeded for liquid starter fertilizer applied during April planting. Early season 2021 irrigation due to extremely dry soil conditions may have alleviated this response at the irrigated site. Contrasts assessing grain yield of N fertilizer treatments in comparison to NTC were insignificant across all site years suggesting maximum yields were attainable through BNF contributions and current soybean cultivars did not require supplemental N fertilizer under the conditions of this study.

Biological N fixation

Over the last several decades and in certain environments, increased soybean productivity (i.e., grain yield, protein, oil) is widening the gap between BNF contributions and total N requirements while simultaneously increasing energy usage by BNF (Rincker et al., 2014; Ciampitti & Salvagiotti, 2018). April planting increased 21-NI R2 and 22-NI R6 NDFA values. However, grain yields were not significantly affected from changes in BNF indicating future improvements focused on fixation may have little impact on grain yield. Planting date had no impact on NDFA contributions during either irrigated site year. While BNF was not increased, it was also not decreased by applying N-P-S as 5x5 starter fertilizer (liquid or granular) across any of the four site years, suggesting further opportunities for lower rates of N fertilizer as starter on soybeans (Table 2.08, Table 2.07). However, previous research evaluating genotypic differences in N-uptake patterns from the soil N fraction and BNF has shown that N-use and BNF contributions differ among timing and source (NO_3 and NH_4) between genotypes (Morro Rosso et al., 2023), suggesting genotype selection may be a better indicator for N use manipulation than planting date.

Contributions from NDFA at R6 ranged between 25-60% under irrigation and 13-55% without irrigation. Reductions in NDFA were associated with N-fertilization occurring pre-plant or at V4 while NTC and starter fertilizer fell within the range described by Ciampitti & Salvagiotti (2018) of 44-72%. Starter fertilizer (liquid or granular) containing 28 kg ha^{-1} N did not reduce N-fixation measured at R2 or R6 while simultaneously increasing early season DM accumulation. Inconsistent N-fixation data under irrigation are likely due to contrasting moisture regimes between 2021 and 2022 (Table 2.02). Contrasts assessing starter fertilizer impacts on RAU were insignificant across all site years confirming no BNF reductions from starter fertilizer usage and further validating N^{15} results (Table 2.11).

Pre-plant, V4, and R2 N applications provided season-long soybean growth impacts as these treatments were unable to recover stem ureide concentrations back to NTC levels by R6. Contrasts show N application at any of the timings evaluated in the current study reduced R6 NDFA (21-I = -4.6%, 22-I = -15.9%, 21-NI = -14.5%, 22-NI = -10.6%) and RAU (21-I = -1.7%, 22-I = -2.7%, 21-NI= -3.2%, 22-NI = -3.1%) as compared to the NTC across all locations (Table 2.10, Table 2.11). However, N application at R2 only significantly reduced R6 NDFA at one site year (22-I). This was not unexpected as maximum N-fixation occurs at R3 leaving little time for soil-applied N to offset BNF contributions (Bender et al., 2015; Brar & Lawley, 2020; Ciampitti et al., 2021). While early reproductive-stage N application to soybeans may not reduce NDFA, ureide abundance testing at R6 showed significant reductions of R2 N treatments compared to NTC across all four site years. Ureide reductions indicate R2 N fertilizer began to reduce N-fixation, but plant impact was minimal as NDFA levels were already well established thus failing to have major implications on grain fill. Nodule counts at R4 did not share treatment differences found by NDFA or RAU analysis at R2 or R6 indicating that the number of nodules produced per plant may not be a sufficient indicator for explaining BNF contributions (Table 2.05).

Previous research indicates grain yield > 4500 kg ha^{-1} (i.e., irrigation or no irrigation) may impact plant N uptake and the ratio between N derived from N-fixation and N contributions from soil fractions including mineralization (Ciampitti & Salvagiotti, 2018). In 2021, all treatment mean grain yields were > 4500 kg ha^{-1} regardless of irrigation while the 22-NI location did not surpass this yield threshold (Table 2.04). Despite 21-I grain yields being merely < 700 kg ha^{-1} greater than 21-NI, a notably different BNF response occurred at each location. While R6 NDFA declined from PPI and V4 N at each location, the non-irrigated site only accumulated 13 and 20% NDFA for the PPI and V4 N timings while the irrigated environment accumulated 50 and 48%, respectively (Table 2.06). Levels of NDFA were similar between locations in 2022 likely due to sufficient early season (April-May) precipitation and lack of initiating irrigation until mid-June. Lower 2022 NDFA values for N-treated plots suggest inhibition of N_2 fixation from fertilizer application. Previous research suggests the best environmental indicators for predicting yield to be planting date and organic matter concentration, while RAU ranked in lower importance (de Borja Reis et al., 2021). Therefore, future improvements in RAU or NDFA may not ultimately result in greater yield.

The energy costs associated with rhizobia symbiosis and conversion of atmospheric N_2 into NH_3 may be more costly than access to soil nitrate availability via soil water mass flow. The energy required to fix one single N2 molecule to NH3 costs leguminous plants 16 ATP (Burris and Roberts, 1993; Cherkasov et al., 2015). Andrews et al. (2009) estimated the energy required for N uptake from BNF sources to be 5-7% greater than that of soil-borne nitrate and ammonium or ~96-98 ATP in place of 92 ATP (Schubert, 1982). Although N uptake from BNF requires more energy than soil-borne N, estimations of > 60,000 Kj kg^{-1} are required to produce, package, transport, and apply N per kg as fertilizer (Lorenz & Morris, 1995; Gellings & Parmenter, 2009). Practitioners must continue to evaluate not only the economic cost of N application but the collective costs of N production including environmental and societal costs and how these characteristics fit into the realm of soybean sustainability.

Dry Matter Accumulation

April planting occurred 24 and 21 days before May planting in 2021 and 2022, respectively. Planting > 20 d earlier increased V4DM across all site years except 22-I (data not shown). Despite April planting increases to early season DM, R2DM measurements reversed with May exceeding April. Data suggest the physiological stage of May planted soybeans during late June combined with early July weather patterns including adequate soil moisture and peak soil N mineralization were more efficient for DM accumulation. Planting into optimal conditions can shorten the lag phase of early season vegetative development that early planted soybeans must overcome (Gaspar et al., 2017). April planted R8TDM was greater than May due to prolonged reproductive stage DM accumulation including increased seed yield from earlier planting. The 22-NI location experienced the same R2DM conditions, but planting timing did not impact R8TDM due to deficit precipitation (i.e., > 10% below the 30-yr average) from July-September limiting earlier planted DM accumulation during the mid to late reproductive stages.

Fertilizer treatments applied pre-V4 (i.e., non-fertilized, granular 5x5, liquid 5x5, and PPI N) affected early season DM production in 21-I, 21-NI, and 22-NI site years. Orthogonal contrasts comparing the addition of 5x5 starter fertilizers to NTC show increased V4DM from starter fertilizer during 21-I,21-NI, and 22-NI (Table 2.10, Table 2.11). Contrasts comparing 5x5 starter fertilizer during April planting and May planting show at non-irrigated locations, starter fertilizer generated greater V4DM during April planting than in May. However at the 21-I location, 5x5 starter fertilizer generated greater V4DM for May planted soybeans. This response is likely due to increased nutrient availability from 24mm irrigation supplied in May to combat extremely dry conditions following May planting. Nitrogen application on average did not outperform NTC at any site year for V4 or R8 DM accumulation (Table 2.10, Table 2.11). The absence of DM response to N-application is not surprising as soybean plants are not inherently deficient in nitrogen due to contributions from BNF, soil N supply, mineralization, and atmospheric deposition (Cafaro La Menza et al., 2019).

Economic Analysis

Practitioners must begin measuring energy input-output relationships for cropping systems more economically rather than utilizing yield increases to justify greater fertilizer input (Gellings & Parmenter, 2009). The spatial variability of Michigan soils allows ample opportunities for site-specific nutrient management. Rising energy costs increase the cost of N fertilizer production and transportation as well as awareness surrounding the social and economic issues regarding excess nitrogen in the environment (Zhang et al., 2015). Mean April 2022 prices of nitrogen and phosphate fertilizers increased 78% and 57%, respectively, compared to April 2021 (data not shown). Price volatility resulted in 57-94% increased application costs between site years. April planted soybeans increased yield during one irrigated site year, suggesting that cultural management practices with no input costs could have a greater impact on the net profitability of irrigated cropping systems rather than non-irrigated (Table 2.12).

Neither starter fertilizer nor in-season nitrogen application increased profitability. Orthogonal contrast analysis of net profitability demonstrated granular starter fertilizer being more profitable than liquid across both irrigated site years, and one of two non-irrigated site years (Table 2.10, Table 2.11). Non-fertilized treatments, however, generated greater income than either starter fertilizer treatment across all four site years indicating the yield benefits of starter fertilizer did not offset associated costs. All evaluated N application timings significantly reduced net income from NTC in three of four site years suggesting environmental conditions along with supplemental irrigation in 2022 may have been adequate for providing sufficient N. Contrasts evaluating starter fertilizer and N application indicate no impact on profitability in non-irrigated environments again suggesting that soil mineralization and BNF were sufficient in these environments.

Conclusions

Over the past several decades, increased soybean yields have expanded the difference between plant N demand and N contributed from BNF. Results from the current study indicate irrigated and non-irrigated sites receiving liquid and granular starter fertilizers with N rates < 28 kg ha^{-1} did not negatively influence BNF, while N applications > 112 kg ha^{-1} at PPI, or V4 negatively impacted BNF in every site year. Nitrogen application at R2 did not negatively effect R6 NDFA at either site in 2021, but RAU was significantly reduced from NTC and starter fertilizer treatments suggesting N fertilizer was entering plants and not negatively influencing BNF due to being too late in the growing season to provide yield benefits beyond the NTC. Supplemental N fertilizer > 112 kg ha^{-1} replaced BNF contributions in all four site years without any benefit to grain yield in three of four site years suggesting even under the high-yield environments tested, BNF individually was able to supply adequate N. Planting date had less effect on BNF than fertilizer strategy, but April planting did improve non-irrigated R2 NDFA and R6 NDFA in 2021 and 2022, respectively. April planting improved grain yield during the 2021 irrigated site year but this may have been attributed to early season irrigation directed to mitigate extremely dry May planting conditions. Either with or without supplemental irrigation, the addition of starter 5x5 fertilizer did not improve yields beyond NTC regardless of April or May planting dates. Due partially to increased fertilizer prices of the strategies evaluated, no treatment produced a return on investment greater than NTC. While 5x5 starter and N fertilizers may accelerate early to mid-season plant growth, none provided yield benefit beyond that of what was supplied by BNF alone when soil test levels are not deficient. Producers should continue to consider pre-plant soil nutrient concentrations and evaluate soil characteristics to not only maintain critical nutrient levels but also consider environmental conditions when contemplating spring planting dates.

LITERATURE CITED

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APPENDIX

Table 2.01. Soil physical and chemical properties and mean P, K, Ca, Mg, and S soil (0-20 cm) nutrient concentrations obtained prior to soybean planting, Lansing, MI, 2021-2022.

		Soil test values†							
Site	Year	pH	CEC	SOM	P	K	Mg	Ca	S
			cmolc kg^{-1}	g kg^{-1}	-------------- mg kg^{-1} --------------				
Irrigated	2021	6.9	7.9	22	55	106	235	900	9
	2022	7.4	13.8	28	145	147	135	2450	17
Non-irrigated	2021	7.0	8.9	22	34	107	280	1250	9
	2022	6.7	8.5	19	37	86	165	1150	8

† pH (1:1, soil/water); SOM soil organic matter (loss-on-ignition); P, phosphorus (Bray-P1); K, potassium (ammonium acetate extractable K); S, sulfur (monocalcium phosphate extraction).

Table 2.02. Mean monthly† 30-yr average‡ precipitation and temperature for the soybean growing season, Lansing, MI 2021-2022.

Year	Apr.	May	Jun.	Jul.	Aug.	Sep.	Total	Jul.-Sep.
	------------------ cm ------------------							
2021	3.45	2.16	16.69	9.50	13.44	8.48	53.72	Excessive§
Irrigation	--	*2.03*	*2.79*	*1.52*	*5.08*	*1.27*	*12.70*	--
2022	7.65	6.07	4.22	4.52	8.23	5.69	36.37	Deficit
Irrigation	--	--	*7.49*	*9.27*	*3.18*	--	*19.94*	--
30-yr avg. ‡	8.28	9.30	9.55	7.47	8.84	7.14	50.57	--
	------------------ ºC ------------------							--
2021	9.0	13.8	21.1	21.4	22.3	17.8	--	--
2022	7.0	16.2	20.2	22.0	21.5	17.3	--	--
30-yr avg	8.3	14.7	20.0	22.1	21.1	16.9	--	--

† Precipitation and temperature data were collected from MSU Enviro-weather (https://enviroweather.msu.edu/).
‡ 30-yr means were obtained from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals).
§ Cumulative precipitation Jul.-Sep. is considered normal if within 10% of 30-yr. mean, deficit if ≥ 10% below 30-yr. mean, and excessive if ≥ 10% above 30-yr. mean.

Table 2.03. Analysis of variance results for soybean response to planting date and fertilizer strategy across irrigated and non-irrigated site years, Lansing, MI, 2021-2022.

Site		**Planting Date x Fertilizer**	**Planting Date**	**Fertilizer**
Irrigated 2021	V4 Dry Matter	0.93	**0.02***	**0.09**
	R2 Dry Matter	0.83	**0.09**	**0.04**
	R2 N^{15}	0.27	0.26	**<0.01**
	R2 RAU	0.19	0.62	**<0.01**
	R6 N^{15}	0.75	0.59	**<0.01**
	R6 RAU	0.73	0.14	**<0.01**
	Grain Yield	0.50	**0.07**	0.18
	Net Profit	0.48	**0.09**	**<0.01**
Non-irrigated 2021	V4 Dry Matter	0.15	**0.04**	**<0.01**
	R2 Dry Matter	0.29	**0.02**	**0.01**
	R2 N^{15}	**0.04**	0.95	**<0.01**
	R2 RAU	**0.08**	0.33	**<0.01**
	R6 N^{15}	0.43	0.77	**<0.01**
	R6 RAU	0.25	**0.07**	**<0.01**
	Grain Yield	0.83	0.19	0.20
	Net Profit	0.83	0.21	**<0.01**
Irrigated 2022	V4 Dry Matter	0.70	0.23	0.40
	R2 Dry Matter	0.73	0.55	0.64
	R2 N^{15}	0.12	0.99	**<0.01**
	R2 RAU	0.83	0.93	**<0.01**
	R6 N^{15}	0.64	0.42	**<0.01**
	R6 RAU	0.37	0.24	**<0.01**
	Grain Yield	0.52	0.81	**<0.01**
	Net Profit	0.53	0.81	**0.02**
Non-irrigated 2022	V4 Dry Matter	0.82	**<0.01**	**<0.01**
	R2 Dry Matter	0.25	**0.09**	0.27
	R2 N^{15}	0.58	0.47	**<0.01**
	R2 RAU	0.37	0.37	**<0.01**
	R6 N^{15}	0.93	**0.05**	**<0.01**
	R6 RAU	016	0.51	**<0.01**
	Grain Yield	0.59	0.55	0.90
	Net Profit	0.59	0.55	**0.04**

* Bolded values significant α=0.10 probability level by GLIMMIX-SAS procedure.

† Nitrogen derived from the atmosphere.

‡ Relative Abundance of Ureides.

Table 2.04. Soybean grain yield† as affected by planting date and fertilizer application across irrigated and non-irrigated site years, Lansing, MI, 2021-2022.

	2021		2022	
Treatment	**Irrigated**	**Non-irrigated**	**Irrigated**	**Non-irrigated**
	——— kg ha^{-1} ———			
Planting Date§				
April	5535 a‡	4896 a	4654 a	4270 a
May	5111 b	4694 a	4593 a	4116 a
P > F	**0.07**	**ns**	**ns**	**ns**
Fertilizer				
NTC	5320 a	4882 a	4651 bc	4123 a
Granular 5x5	5481 a	5091 a	4613 abc	4338 a
Liquid 5x5	5252 a	4755 a	4311 c	4129 a
PPI N	5528 a	4634 a	4896 a	4237 a
V4 N	5273 a	4735 a	4775 abc	4116 a
R2 N	5481 a	4674 a	4788 ab	4203 a
P > F	**ns**	**ns**	**<0.01**	**ns**

† Grain yield adjusted to 135 g kg^{-1} moisture.

‡ Least square means within the same column followed by the same lowercase letter are not significantly different at α=0.1.

§ April and May planting dates represent April 23 and May 17, 2021, and April 29 and May 20, 2022.

Table 2.05. Mean R4 nodule counts per plant as influenced by planting date and fertilizer strategy across irrigated and non-irrigated soybeans, Lansing, MI, 2021-2022.

Site	Treatment	2021	2022
Irrigated	Planting Date‡	—— nodules plant^{-1} ——	
	April	94 a *	75 a
	May	73 b	77 a
	P > F	**0.09**	**ns**†
	Fertilizer		
	NTC	86 a	98 a
	Granular 5x5	93 a	61 a
	Liquid 5x5	88 a	77 a
	PPI N	73 a	62 a
	V4 N	72 a	87 a
	R2 N	89 a	72 a
	P > F	**ns**	**ns**
Non-Irrigated	Planting Date		
	April	88 a	47 a
	May	56 b	54 a
	P > F	**0.03**	**ns**
	Fertilizer		
	NTC	94 a	42 a
	Granular 5x5	76 ab	55 a
	Liquid 5x5	69 ab	67 a
	PPI N	59 b	32 a
	V4 N	70 ab	51 a
	R2 N	65 ab	56 a
	P > F	**0.07**	**ns**

* Least square means within the same column followed by the same lowercase letter are not significantly different at α=0.1.

† ns = not significantly different at α=0.10.

‡ April and May planting dates represent April 23 and May 17, 2021, and April 29 and May 20, 2022.

Table 2.06. Irrigated and non-irrigated soybean planting date and fertilizer application main effects on R2 and R6 N^{15} and relative abundance of ureides, Lansing, MI, 2021.

Site	Treatment	R2 N^{15}	R6 N^{15}	R2 RAU†	R6 RAU
Irrigated	Planting Date	%			
	April 23	25.13 a*	56.57 a	69.83 a	93.55 a
	May 17	19.78 a	55.02 a	68.33 a	92.75 a
	P > F	**ns‡**	**ns**	**ns**	**ns**
	Fertilizer				
	NTC	28.30 a	57.67 a	73.29 ab	93.83 ab
	Granular 5x5	28.39 a	60.32 a	77.28 a	94.75 a
	Liquid 5x5	25.64 a	57.77 a	73.86 ab	94.01 ab
	PPI N	13.50 b	50.13 b	66.99 b	93.03 ab
	V4 N	16.44 b	48.36 b	53.99 c	92.75 b
	R2 N	-- §	60.53 a	--	90.54 c
	P > F	**<0.01**	**<0.01**	**<0.01**	**<0.01**
Non-Irrigated	Planting Date				
	April 23	¶	36.73 a	¶	93.57 a
	May 17		36.10 a		92.13 b
	P > F		**ns**		**0.08**
	Fertilizer				
	NTC		41.40 a		94.23 a
	Granular 5x5		47.94 a		94.76 a
	Liquid 5x5		48.32 a		94.98 a
	PPI N		12.68 b		90.79 b
	V4 N		19.68 b		91.65 b
	R2 N	--	48.58 a		90.64 b
	P > F		**<0.01**		**<0.01**

* Least square means within the same column followed by the same lowercase letter are not significantly different at α=0.1.

† Relative Abundance of Ureides.

‡ ns = not significant at α=0.1.

§ Treatment not an effect at time of sampling.

¶ Planting date x fertilizer interaction of R2 N^{15} and R2 RAU.

Table 2.07. Soybean planting date and fertilizer application effects on irrigated and non-irrigated R2 and R6 N^{15} and relative abundance of ureides, Lansing, MI, 2022.

Site	Treatment	R2 N^{15}	R6 N^{15}	R2 RAU †	R6 RAU
Irrigated	Planting Date		%		
	April 29	39.5 a*	40.5 a	71.8 a	94.7 a
	May 20	39.5 a	37.1 a	71.2 a	94.0 a
	P > F	**ns‡**	**ns**	**ns**	**ns**
	Fertilizer				
	NTC	46.2 ab	46.3 a	80.6 a	95.9 a
	Granular 5x5	33.4 cd	46.3 a	75.7 a	95.4 a
	Liquid 5x5	40.4 bc	48.9 a	77.1 a	95.4 a
	PPI N	27.9 d	30.3 c	61.3 b	93.7 b
	V4 N	49.8 a	25.8 c	62.9 b	93.3 b
	R2 N	-- §	35.1 bc	--	92.5 b
	P > F	**<0.01**	**<0.01**	**<0.01**	**<0.01**
Non-Irrigated	Planting Date				
	April 29	45.9 a	51.0 a	82.7 a	92.8 a
	May 20	43.2 a	42.5 b	78.7 a	92.5 a
	P > F	**ns**	**0.05**	**ns**	**ns**
	Fertilizer				
	NTC	43.0 bc	51.8 ab	85.8 a	94.2 a
	Granular 5x5	44.4 bc	50.6 ab	83.5 a	94.0 a
	Liquid 5x5	45.7 ab	54.7 a	84.5 a	94.3 a
	PPI N	35.7 c	31.8 c	71.1 b	91.3 b
	V4 N	54.0 a	38.8 bc	78.5 b	90.2 b
	R2 N	--	52.9 ab	--	91.8 b
	P > F	**<0.01**	**<0.01**	**<0.01**	**<0.01**

* Least square means within the same column followed by the same lowercase letter are not significantly different at $\alpha=0.1$.

† Relative Abundance of Ureides.

‡ ns = not significant at $\alpha=0.1$.

§ R2 N treatment not an effect at time of sampling.

Table 2.08. Interaction between planting date and fertilizer strategy on R2 N^{15} non-irrigated soybean, Lansing, MI, 2021.

	Planting Date		***P > F***
Fertilizer	April 23	May 17	
	%		
NTC	37.53 a†A‡	30.86 aA	**0.30**
Granular 5x5	31.20 aBA	37.70 aA	**0.31**
Liquid 5x5	35.40 aA	39.47 aA	**0.52**
PPI N	22.69 aB	7.50 bB	**0.05**
V4 N	24.33 aB	34.31 aA	**0.12**
R2 N	--*	--	
P > F	**0.04**	**<0.01**	

* Treatment not yet applied in field.

† Means in the same row followed by the same lowercase letter are not significantly different at α=0.10.

‡ Means in the same column followed by the same uppercase letter are not significantly different at α=0.10.

Table 2.09. Interaction between planting date and fertilizer strategy on R2 relative abundance of ureides non-irrigated soybeans, Lansing, MI, 2021.

	Planting Date		***P > F***
Fertilizer	April 23	May 17	
	%		
NTC	79.23 a†A‡	80.88 aA	**0.72**
Granular 5x5	70.10 bB	83.15 aA	**<0.01**
Liquid 5x5	79.98 aA	80.58 aA	**0.90**
PPI N	61.95 aC	55.53 aB	**0.17**
V4 N	50.60 aD	53.58 aB	**0.52**
R2 N	--*	--	
P > F	**<0.01**	**<0.01**	

* Treatment not yet applied in field.

† Means in the same row followed by the same lowercase letter are not significantly different at α=0.10.

‡ Means in the same column followed by the same uppercase letter are not significantly different at α=0.10.

Table 2.10. Soybean dry matter accumulation, N[15], relative abundance of ureides, yield, and net profitability response using single degree of freedom contrasts across irrigated and non-irrigated environments, Lansing, MI, 2021.

Contrast†	Dry Matter Accumulation		Nitrogen Derived from the Atmosphere		Relative Abundance of Ureides		Yield	Net Profit
	V4	R8	R2	R6	R2	R6	Harvest	
				Irrigated				
Liquid 5x5 vs. granular 5x5	ns	ns	ns	ns	ns	ns	**0.09**	**0.03**
Starter vs. NTC	**0.07***	ns	ns	ns	ns	ns	ns	**<0.01**
N application vs. NTC	ns	ns	ns	**0.03**	ns	**<0.01**	ns	**<0.01**
April starter vs. May starter	**<0.01**	ns	ns	ns	ns	ns	**0.09**	**0.09**
N application April PD vs. N application May PD	ns	**0.02**	ns	ns	ns	ns	**0.03**	**0.03**
				Non-irrigated				
Liquid 5x5 vs. granular 5x5	ns	**0.04**	ns	ns	ns	ns	**0.06**	**0.04**
Starter 5x5 vs. NTC	**<0.01**	ns	ns	**0.03**	ns	ns	ns	**0.04**
N application vs. NTC	ns	ns	ns	**<0.01**	ns	**<0.01**	ns	**<0.01**
April starter vs. May starter	**<0.01**	**0.03**	ns	ns	**0.05**	ns	ns	ns
N application April PD vs. N application May PD	ns	**0.02**	ns	ns	ns	**<0.01**	ns	ns

* Numeric P-values significantly increased at $\alpha=0.10$ using single-degree-of-freedom contrasts.
† ‘Liquid 5x5 vs. granular 5x5’ compares liquid 5x5 and granular 5x5 treatments from each planting date against each other, ‘starter vs. NTC’ compares both liquid and granular 5x5 starters combined from each planting date against NTC, ‘N application vs. NTC’ compares PPI, V4 and R2 N treatments combined from each planting date against NTC, ‘April starter vs May starter’ compares liquid and granular 5x5 starters in April against liquid and granular 5x5 starters in May, ‘N application April PD vs. N application May PD’ compares PPI, V4 and R2 N treatments combined of April planted against PPI, V4 and R2 N treatments of May planted.

Table 2.11. Soybean dry matter accumulation, N^{15}, relative abundance of ureides, yield, and net profitability response using single degree of freedom contrasts across irrigated and non-irrigated environments, Lansing, MI, 2022.

Contrast†	Dry Matter Accumulation		Nitrogen Derived from the Atmosphere		Relative Abundance of Ureides		Yield	Net Profit
	V4	R8	R2	R6	R2	R6	Harvest	
				Irrigated				
Liquid 5x5 vs. granular 5x5	ns	ns	**0.06**	ns	ns	ns	**0.09**	**0.04**
Starter vs. Control	ns	ns	**<0.01**	ns	ns	ns	ns	**<0.01**
N application vs. Control	ns	ns	ns	**<0.01**	ns	**<0.01**	**<0.01**	ns
April starter vs. May starter	ns	ns	ns	ns	ns	ns	ns	ns
N application April PD vs. N application May PD	ns	ns	ns	ns	ns	**0.02**	ns	ns
				Non-irrigated				
Liquid 5x5 vs. granular 5x5	**0.05**	ns	ns	ns	ns	ns	ns	ns
Starter 5x5 vs. Control	**<0.01**	**0.03**	ns	ns	ns	ns	ns	**0.02**
N application vs. Control	ns	ns	ns	**<0.01**	ns	**<0.01**	ns	**<0.01**
April starter vs. May starter	**<0.01**	ns	ns	**0.05**	ns	ns	ns	ns
N application April PD vs. N application May PD	ns	ns	ns	**0.01**	ns	ns	ns	ns

* Numeric P-values significantly increased at α=0.10 using single-degree-of-freedom contrasts
† 'Liquid 5x5 vs. granular 5x5' compares liquid 5x5 and granular 5x5 treatments from each planting date against each other, 'starter vs. NTC' compares both liquid and granular 5x5 starters combined from each planting date against NTC, 'N application vs. NTC' compares PPI, V4 and R2 N treatments combined from each planting date against NTC, 'April starter vs May starter' compares liquid and granular 5x5 starters in April against liquid and granular 5x5 starters in May, 'N application April PD vs. N application May PD' compares PPI, V4 and R2 N treatments combined of April planted against PPI, V4 and R2 N treatments of May planted

Table 2.12. Soybean planting date and fertilizer application effects on economic return† across irrigated and non-irrigated site years, Lansing, MI, 2021-2022.

	2021		2022	
Treatment	**Irrigated**	**Non-irrigated**	**Irrigated**	**Non-irrigated**
	US$ ha^{-1}			
Planting Date§				
April	2288 a‡	2006 a	2011 a	1750 a
May	2162 b	1920 a	1984 a	1826 a
P > F	**0.09**	**ns**	**ns**	**ns**
Fertilizer				
NTC	2350 a	2157 a	2118 a	2006 a
Granular 5x5	2259 ab	2088 ab	1987 ab	1851 ab
Liquid 5x5	2128 b	1908 b	1804 b	1720 ab
PPI N	2268 ab	1871 b	2073 a	1752 ab
V4 N	2128 b	1890 b	1999 ab	1678 b
R2 N	2219 ab	1863 b	2004 ab	1722 ab
P > F	**<0.01**	**<0.01**	**0.02**	**0.04**

† Economic return calculated as ((soybean grain price x grain yield) – (fertilizer + application)).
‡ Least square means within the same column followed by the same lowercase letter are not significantly different at α=0.1.
§ April and May planting dates represent April 23 and May 17, 2021, and April 29 and May 20, 2022.

Table 2.13. Return on fertilizer investment (%) as compared to non-fertilized control, Lansing, MI, 2021-2022.

	2021		2022	
Treatment	**Irrigated**	**Non-irrigated**	**Irrigated**	**Non-irrigated**
	%			
Fertilizer				
NTC	--*	--	--	--
Granular 5x5	96.1†ab‡	96.8 ab	93.8 ab	92.3 ab
Liquid 5x5	90.6 b	88.5 b	85.2 b	85.7 ab
PPI N	96.5 ab	86.7 b	97.8 a	87.3 ab
V4 N	90.6 b	87.6 b	94.4 ab	83.6 b
R2 N	94.4 ab	86.4 b	94.6 ab	85.8 ab

* Non-fertilized treatments normalized at 100%.
† Values within the same column produced less ROI than non-fertilized if <100% and greater ROI than non-fertilized if > 100%.
‡ Values within the same column followed by the same lowercase letter are not significantly different at α=0.1.

CHAPTER 3: SUGARBEET VARIETAL RESPONSE TO FERTILIZER STRATEGY AND HARVEST TIMING

Abstract

Winter climate variability including increased freeze-thaw cycling enhances sugarbeet decomposition during open pile storage reducing sugar quality. To complete sugar processing prior to warmer spring temperatures, Michigan Sugar Company extended the sugarbeet harvest season by allowing early harvest (i.e., mid-late August) as compared to conventional harvest (mid-late October). A recent initiative to improve sugar quality (i.e., recoverable sucrose near 150 kg Mg^{-1}) but not reduce overall tonnage (i.e., yield near 67 Mg ha^{-1}) has practitioners questioning which cultural and fertilizer management strategies to target across multiple harvest intervals. A multi-year field study was established to investigate both early and conventional harvest timings on two contrasting varieties (aggressive vs. defensive) and five fertilizer strategies. Fertilizer strategies consisted i) non-treated control (NTC), ii) 67 kg N ha^{-1} applied 5x5 at planting (5x5 N only), iii) 67 kg N ha^{-1} applied 5x5 followed by 112 kg N ha^{-1} subsurface banded at 2-4 leaf growth stage for total N rate of 179 kg N ha^{-1} (5x5 + Sidedress N), iv) 67 kg N ha^{-1} applied 5x5 followed by 112 kg K_2O ha^{-1} Monty's® LiquidK2O® (Monty's Plant Food, Louisville, KY) above surface banded at 20-leaf growth stage (5x5 + liquid K), v) 67 kg N ha^{-1} applied 5x5 followed by 112 kg N ha^{-1} subsurface banded at 2-4 leaf growth stage as well as 112 kg K_2O ha^{-1} Monty's® LiquidK2O® surface banded at 20-leaf growth stage for a total of 179 kg N ha^{-1} and 112 kg K_2O ha^{-1} (All). Across early and conventional harvest timings, 179 kg N ha^{-1} produced optimal root yields and recoverable sucrose per hectare but peak recoverable sucrose per Mg was produced by starter N only in both years of early harvest timing and one of two years for conventional harvest timing. Liquid K_2O application to either starter N only or split-

applied N did not increase root yield or quality from similar treatments receiving only N fertilizer suggesting K management may be part of a broader soil management strategy for areas with below critical K concentrations rather than specifically targeted to enhance sugar production.

Introduction

Michigan sugarbeet growers experienced a > 30% increase in root yields over the past decade with average yields of 83.8 Mg ha^{-1} across approximately 57,465 hectares are beginning to create sugar processing difficulties (NASS, 2021). Sugarbeet production in Michigan often involves open piling storage grounds until processing (Hoffmann et al., 2013). Increased production volume lengthens the time required to complete a processing campaign which can carry into the springtime freeze-thaw cycle resulting in pile spoilage and waste.

Although increased root yields can generate greater grower profitability, sucrose concentrations declined by 11% from 2008 to 2018 (NASS, 2022; Purucker & Steinke, 2022). In order to maintain sugar throughput and lessen processing time, Michigan Sugar Company (MSC) developed a new goal to normalize tonnage production around 67 Mg ha^{-1} and recoverable sucrose per Mg near 150 kg Mg^{-1} (Flegenheimer, 2019). By allotting a certain quantity of hectares for an early harvest (e.g., mid-to-late August), factories lengthen the processing campaign allowing for fresh processing of sugarbeets until autumn weather allows for permanent piling. While early harvest is not necessarily a new processing strategy, identifying agronomic practices that benefit earlier harvest may be an advantage to both producers and processors. Early harvested beets typically have reduced sucrose concentration and root yield, so growers receive a premium for early sugar delivery (DeBruyn et al., 2017). Previously, conventional harvest timings yielded approximately 22% more tonnage, 15% greater sucrose content, and 45%

greater recoverable white sugar than early harvest (Lauer, 1997). Agronomic management practices may require revisions to compensate for sugarbeets harvested prior to late-season bulking.

Genotype selection may be one way to manipulate end-of-season sucrose content prior to planting. While the germplasm available for sugarbeet is lesser than other crops, combined efforts between private and commercial breeders have increased yield potential and disease resistance (Panella et al., 2015). Halvorson & Hartman (1980) suggested genotypic differences may require different cultivar strategies and multiple harvest timings to maximize sucrose production. In Wyoming, Lauer (1997) planted and harvested cultivars at various timings and found high root yield genotypes (i.e., aggressive variety) should be harvested later, while high sucrose genotypes should be utilized for early harvest. Disease resistance (i.e., defensive variety) may also warrant consideration as early harvested fields will not continue growing late into the season minimizing disease occurrence, and cultivars with high disease resistance often contain decreased sucrose concentrations that require the full growing season to mature (Smith & Campbell, 1996). Shane & Teng (1992) recommended planting *Cercospora beticola Sacc.* susceptible varieties and applying fungicides as needed to maximize profitability rather than lower production with disease-resistant varieties. In Europe, Hoffmann et al. (2009) showed the sugar concentration responses by differing genotypes were contrary to other quality factors suggesting that sugarbeet roots may be at the physiological storage potential at nearly 20% sucrose regardless of harvest timing or fertilizer practices. Sugarbeet roots are vegetative storage organs that are not constrained by any one growth stage (i.e., cereal crops during grain fill) but rather are limited by above-ground photosynthesizing growth factors (Hoffmann et al., 2009; Schnepel & Hoffmann, 2016). However, trials evaluating cultivar storability suggested cultivar selection may be utilized to manipulate sucrose production to complement current processing abilities (Kenter & Hoffmann, 2009; Campbell & Klotz, 2007; Van Eerd et al., 2012).

Regardless of harvest timing, proper nutrient management is critical to sugarbeet production. Early season nitrogen (N) deficiencies may inhibit root yield and sucrose production, but late N applications can reduce sucrose purity leading to different grower management philosophies (Stevanato et al., 2010; Norton, 2011). When asked at a recent Michigan sugarbeet diagnostic day grower preference to be N-short or N-excess heading into mid-season, pre-tour response was split 40:60 too little vs. too much, respectively, while post-tour response was 70:30 too little vs. too much, respectively (Wilbur et al., 2022). In the great lakes beet growing region, annual N mineralization takes place primarily in the summer months (i.e., June-August), but differ in quantity year-to-year based on weather patterns making regionally accepted N rates difficult to quantify (Christenson & Butt, 2008). Current MSC and MSU recommendations suggest 45-56 kg N ha^{-1} should be used in a starter 5x5 (5cm below and 5cm laterally from seed furrow) at planting (Warncke et al., 2009; Steinke & Bauer, 2017; Purucker & Steinke, 2022). The remaining N is often applied either pre-plant or sidedressed during early vegetative production (i.e., 2-4 leaf growth stage), but the total N necessary may require adjustments based on harvest timing or cultivar selection (Lauer, 1995; Steinke & Bauer, 2017; Purucker & Steinke, 2022). Industry standards for total N rate in Michigan are currently 180 kg N ha^{-1} (MSC, 2020). Optimal N rates are achieved when N is utilized early in the growing season, leaving the rhizosphere N-depleted near harvest (Wu et al., 1976). However, earlier harvest timings generally reduce N use efficiencies either leaving residual N in foliage, as impurities in the root, or remaining in the field after harvest and subject to environmental loss (DeBruyn et al., 2017). DeBruyn et al. (2019) found that N-treated plots produced 15-20 Mg ha^{-1} greater yields than non-fertilized plots regardless of fertilizer source or placement. Lauer (1995) observed a harvest date by N rate interaction concluding that N rate should decrease for early harvest and maximum recoverable sucrose. Due to the inverse relationship between root yield and sucrose concentration, recommended N fertilizer rates should focus on maximizing economic return and reducing potential environmental losses (Doney et al., 1981; DeBruyn et al., 2017).

Sugarbeet potassium (K) tissue levels are second only to nitrogen at 1-3% by weight creating interest in K fertilization and more specifically N:K ratios (Prajapati & Modi, 2012). Within the plant, K is transported to the phloem for use as an energy source for transportation throughout the plant including aiding sugar transport from foliage to roots (Dreyer et al., 2017). Potassium functions in sugarbeet include improved osmotic potential of root cells allowing for greater water uptake during periods of deficiency and increased uptake of other mineral elements such as N traveling within water (Abdel-Montgally & Attia, 2009; Mäck et al., 2007; Grzebisz et al., 2013). Terry and Ulrich (1973) found negative effects on photosynthesis and daytime stomatal opening when either K or Na was limited. Although research show when plant tissue K is limited a negative effect on sugarbeet yield and quality follows, few data show a positive impact from K fertilization of low K index soils (Milford et al., 2000). Due to the mica and feldspar content of parent material and high cation exchange capacity of the medium-to-fine textured soils suited for sugarbeet production, many growing regions are typically not K deficient (Mouhamad et al., 2016). Similar to N, K application must be closely monitored regarding sucrose content. Accepted ranges of K concentration in the sucrose extraction process are 700-1000 mg 100 g^{-1} sugar with K concentrations exceeding this threshold becoming an impurity and reducing the amount of recoverable sugar (Milford et al., 2000).

The objective of this study was to evaluate the impacts of two contrasting varieties (i.e., aggressive vs. defensive) and N and K fertilization strategies on root yield, sucrose content, recoverable white sugar per hectare, and recoverable white sugar per megagram across early and conventional harvest timings.

Materials and Methods

Field trials were located at the Saginaw Valley Research and Extension Center near Richville, MI (42º23'57.0" N,83º41'47.7" W) on a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic Typic Epiaquoll) in 2021 and 2022. Fields were autumn chisel plowed (20-cm) following corn and field cultivated (10-cm) in the spring prior to planting sugarbeets. Sites were tile drained, non-irrigated, and contained 0% slope which is representative of sugarbeet production regions across the state. Pre-plant soil (0-20 cm) physical and chemical characteristics followed standard procedures and are listed in Table 3.01. Monthly precipitation and temperature data were collected throughout the growing season from Michigan State University Enviro-weather (http://mawn.geo.msu.edu) (Table 3.02). Temperature and 30-yr means were obtained from the National Oceanic and Atmosphere Administration (NOAA, 2022).

Field experiments were planted on 19 April 2021 and 11 May 2022 with a Monosem planter (Monosem Inc., Kansas City, KS). Plots measured 4.6 m in width and 10.7 m in length containing 6 rows with 76 cm spacing. Trials were arranged as randomized complete-block, split-plot design with two whole plot factors (i.e., variety and harvest timing), and one sub-plot factor (i.e., fertilizer strategy). Varieties utilized were 'Crystal G675' and 'Crystal G919' (ACH Seeds, Inc., Eden Prairie, MN). The evaluated cultivars were classified as 'aggressive' for the high tonnage and sucrose tendencies of C-G675, and 'defensive' for the greater disease resistance observed in C-G919. The two harvest timings targeted a late-August ‘early harvest’ timing and a conventional full-season October harvest timing. Fertilizer strategy included five treatments: i) non-treated control (NTC), ii) 67 kg N ha^{-1} from urea ammonium nitrate applied 5x5 at planting (5x5 N only), iii) 67 kg N ha^{-1} urea ammonium nitrate applied 5x5 followed by 112 kg N ha^{-1} urea ammonium nitrate subsurface banded at 2-4 leaf growth stage for total N rate of 179 kg N ha^{-1} (5x5 + Sidedress N), iv) 67 kg N ha^{-1} urea ammonium nitrate applied 5x5 followed by 112 kg K_2O ha^{-1} Monty’s® LiquidK2O® (Monty’s Plant Food, Louisville, KY) surface banded at 20-leaf growth stage (5x5 + liquid K), and v) 67 kg N ha^{-1} urea ammonium nitrate applied 5x5 followed by 112 kg N ha^{-1} urea ammonium nitrate subsurface banded at 2-4 leaf growth stage as well as 112 kg K_2O ha^{-1} Monty’s® LiquidK2O® surface banded at 20-leaf growth stage for a total of 179 kg N ha^{-1} and 112 kg K_2O ha^{-1} (All). Sidedress N applications were made using a tractor-mounted coulter injection cart placing fertilizer 10 cm below ground directly between sugarbeet rows. Surface band applications of K_2O were made using a backpack sprayer equipped with orifice body nozzles and short drop hoses to place fertilizer 5-10 cm laterally from sugarbeet rows.

Plant stand was counted 20-30 days after emergence and fractional green canopy coverage (FGCC) was taken every 10-14 days until full canopy closure. Normalized difference Vegetation index (NDVI) and chlorophyll meter (SPAD) measurements were taken at 6-8 leaf and 12-14 leaf growth stages to measure early season responses to fertilizer and cultivar selection. Early and conventional harvest timings corresponded to MSC beginning sugar processing operations and initiation of outdoor storage piling, respectively. Beets from the center two rows of each plot were harvested on 25 August and 20 October in 2021 and 29 August and 24 October in 2022 with a mechanical plot harvester and weighed. Subsamples of root (10-15 roots plot^{-1}) were collected and analyzed for sucrose content, sucrose extraction percentage, and recoverable sucrose at the Michigan Sugar Co. (MSC) Laboratory (Bay City, MI).

Economic return was calculated using MSC's average payment standard (2021-2022) which considers delivery date, root yield, and recoverable sucrose (kg Mg^{-1}). In 2021, gross economic return was based on US\$0.3896 kg^{-1} sugar delivered, with harvest date adjustment factors of 1.62 for tonnage and 1.12 for RWST (recoverable white sucrose per tonne) for early harvest and 1.04 for both tonnage and RWST for conventional harvest. In 2022, gross economic return was based on US\$0.3968 kg^{-1} sugar delivered, with harvest date adjustment factors of 1.426 for tonnage and 1.349 for RWST for early harvest and 1.0 for both tonnage and RWST for conventional harvest. Net economic return was calculated by subtracting fertilizer, application, and trucking cost from each treatment. Fertilizer costs were obtained from local elevators and application costs from the Michigan State University Extension Custom Machine and Work Rate Estimates (Stein, 2021). Application costs were US\$7.36, \$27.92, and \$27.92 ha^{-1} for subsurface 5x5 nutrient application, subsurface side-dress application, and surface banding application, respectively (Farm Business Team, MSU, 2021). Fertilizer costs in 2021 were US\$101.41, \$270.26, \$1395.25, and \$1564.10 ha^{-1} but in 2022 were US\$177.82, \$509.16, \$1506.95, and \$1838.29 ha^{-1} for 5x5 only, 5x5 + SD, 5x5 + K and 'All' treatments, respectively. Trucking from field to processor was figured at \$4.13 Mg^{-1} for both years.

Data were analyzed separately by site-year due to significant treatment-by-year interactions and subjected to analysis of variance using the GLIMMIX procedure in SAS 9.4 (SAS Institute Inc., 2017). Replication was considered a random factor while all other factors were considered fixed. Normality of residuals was tested with the UNIVARIATE procedure ($P \leq 0.05$). Pre-harvest data measurables were analyzed as two factors with 8 replications due to harvest timing not yet in effect. Least square means were separated using the LINES option of the slice statement when ANOVA indicated a significant interaction ($P \leq 0.10$). Each site year was analyzed individually due to significant treatment-by-year interactions. Due to previously known yield and sucrose differences between harvest timings, interactions including harvest timing were not evaluated (i.e., conventional harvest yields greater than early). The importance of this study was to evaluate potential fertilizer strategy by variety interactions within each harvest timing. Non-treated control plots were not statistically analyzed with other fertilizer strategies but rather used to validate fertilizer responsiveness.

Results

The current study evaluated two cultivars with differing traits and four fertilizer strategies across both early (i.e., August) and regular (i.e., October) sugarbeet harvest timings. Harvest timing differences were anticipated prior to study initiation and observed in previous research (Lauer, 1997; DeBruyn et al., 2017). Therefore, main effects of harvest timing are not compared against each other (e.g., early vs conventional harvest) in this study but rather used to demonstrate how fertilizer management strategies may require adjustment based upon the length of growing season (i.e., harvest timing). To better evaluate the impacts of cultivar selection and fertilizer strategy, results are discussed based upon data sliced by harvest timing.

Environmental Conditions

Cumulative growing season (April-Sept.) precipitation was deficient (i.e., >10% below the 30-year average) across site years with a 6.2 and 15.4 cm deficit during 2021 and 2022, respectively (Table 3.02). April 2021 mean air temperatures 1.5ºC above and precipitation 80% below the 30-year means hastened spring planting conditions as soil temperatures remained above 10ºC on 27 April. Persistent 2022 April precipitation coupled with air temperatures -1.1ºC below the 30-year mean delayed planting as soil temperatures did not remain above 10ºC until 4 May. Despite planting date and environmental differences between site years, negligible impacts on sugarbeet emergence or early season development occurred. Growing degree day (10ºC base temp) totals were 1160 and 1626 for August and October 2021 harvest, respectively, and 1150 and 1435 for August and October 2022 harvest, respectively.

Harvest Timing

October harvest generated 78 and 32% greater mean root yield and 77 and 64% greater mean recoverable sucrose per hectare than August harvest in 2021 and 2022, respectively (Table 3.03, Table 3.04). Specifically, August harvest produced yields of 45.9 and 63.6 Mg ha^{-1} and 7841 and 7896 kg Mg^{-1} recoverable sucrose in 2021 and 2022, respectively, while October harvest provided significantly greater yields of 81.6 and 84.0 Mg ha^{-1} and 13614 and 12940 kg Mg^{-1} recoverable sucrose in 2021 and 2022, respectively ($P < 0.001$ for all factors). Despite growing degree day accumulation up to August harvest being < 1% different between site years and 2022 precipitation totals 20% lower than 2021, August 2022 harvest produced 17.7 Mg ha^{-1} greater yield than 2021. While 2021 environmental conditions were more favorable for plant growth leading up to August, greater root yields produced in August 2022 may be attributed to a later planting date providing more adequate seed establishment and greater use of starter fertilizer as starter N can increase early season growth rates allowing for earlier root development (Clark et al., 2010). Results emphasize the importance of a “start right to finish well” mentality which can carry through to harvest. Differences between harvest timings were expected, and varietal yield characteristics should be utilized moving forward for developing and refining management plans catered specifically to an anticipated harvest date.

Early Harvest Timing

Cultivar selection influenced root yield and recoverable sucrose per hectare across both site years (Table 3.03). Cultivar C-G675 (i.e., aggressive characteristics) produced 6.1 and 6.9 Mg ha^{-1} and 1145 and 725 kg Mg^{-1} more yield and sucrose than C-G919 (i.e., defensive characteristics) in 2021 and 2022, respectively. On average, August harvest 2022 produced 38.6% more root yield than 2021, but recoverable sucrose per hectare was only 0.7% different between site years. The 2022 growing season accumulated 466 additional growing degree days (+40.2%) prior to August harvest than 2021 and likely contributed to increased root yield. Recoverable sucrose per megagram, sucrose concentration, and extraction purity were not influenced by cultivar in either site year.

Split-applied N (179 kg N ha^{-1}) maximized root yield across both site years compared to starter N alone (67 kg N ha^{-1}) producing 32.6 and 11.5% greater root yield in the 2021 and 2022 growing seasons, respectively (Table 3.03). Split-applied N also produced 2284 kg ha^{-1} (+34.1%) more sucrose than starter N alone in 2021 but there were no significant impacts on sucrose recovery in 2022. Sucrose recovery per megagram and extraction percentage were not affected by fertilizer strategy. On average, treatments receiving starter N provided 22.7% greater root yield than the non-treated control (NTC), while split-applied N produced 36.8% more yield than NTC in 2022. Liquid potassium applications applied individually following starter N or in combination with a split-applied N program at 112 kg K_2O ha^{-1} did not affect root yield, recoverable sucrose, or sucrose concentration.

Conventional Harvest Timing

Cultivar selection did not influence root yield, recoverable sucrose, sucrose concentration, or extraction quality in 2021 (Table 3.04). On average, plots receiving a split-applied N fertilizer strategy experienced increased root yields 23.6 Mg ha^{-1} and recoverable sucrose 3584 kg ha^{-1} when compared to starter N alone. Neither liquid potassium applications applied either individually following starter N or in combination with split applied N affected yield in 2021. In 2022 cultivar selection and fertilizer strategy interacted to affect root yield and recoverable sucrose per hectare (Table 3.05, Table 3.06). Split applied N in conjunction with C-G919 generated 23.0 Mg ha^{-1} root yield and 3682 kg ha^{-1} recoverable sucrose beyond yields obtained from starter N. Data suggest C-G675 may have greater N-use efficiency or shorter duration to sucrose accumulation (i.e., faster growth rate) as starter N alone generated similar yields to split-applied N applications. Split-applied N application was necessary for C-G919 to achieve optimal yield and sucrose production.

Aboveground Vegetation Indices

Canopy closure measurements among cultivars differed between site years (data not shown). In 2021, C-G919 achieved greater canopy closure than C-G675 from the 12-leaf growth stage through full canopy. However in 2022, C-G675 achieved greater canopy closure than C-G919 beginning at the 20-leaf growth stage. The normalized difference vegetation index (NDVI) did not produce significant differences in 2021, but at 6-8 leaf displayed greater greenness levels in 2022 for split-applied N applications as compared to starter N alone ($P = 0.08$). The same values for fertilizer strategy were not significantly different at the 12-14 leaf growth stage, but C-G675 attained greater values than C-G919 ($P < 0.001$).

Effects of Harvest Timing, Cultivar Selection, and Fertilizer Strategy on Net Profitability

In order to equalize net income between early and conventional harvest timings, early harvest delivery premiums must adequately account for root yield and sucrose reductions. In 2021, gross grower payments, net return less trucking, and net return less trucking and fertilizer costs between harvest timings were not significantly different (Table 3.07). However, in 2022, increased October root yield and recoverable sucrose per metric ton generated US$932 ha^{-1} or 15.7% greater grower return on investment than early harvest. For profitability analyses considering fertilizer cost, worth noting was a 70% increase in N cost between the 2021 and 2022 growing seasons and large costs associated with liquid K_2O sources. Cultivar selection interacted with fertilizer strategy in 2021 profitability analyses (Table 3.08, Table 3.09, Table 3.10). Across cultivars, grower return was maximized using split-applied N fertilizer while adding mid-season band applied K did not influence grower profitability. Gross return was increased 14.6% by C-G675 when compared to C-G919 (Table 3.08). No interactions occurred between cultivar and fertilizer strategy on 2022 profitability analyses (Table 3.07). Grower payment in 2022 was significantly increased with the use of C-G675 by US$750 ha^{-1} or 12.4% compared to C-G919. Split-applied N treatments increased gross grower payment 14.1% over those receiving 5x5 starter fertilizer alone. While not statistically analyzed with other data, utilizing 5x5 N only or split-applied N treatments increased 2022 gross income beyond the NTC by $1593 ha^{-1} (40.6%) and by $2040 ha^{-1} (52%), respectively.

Discussion

Regional Sugarbeet Production Considerations

Sugarbeet management is specific to growing region. For example, the Great Lakes region and Red River Valley in western Minnesota and eastern North Dakota are similar in that both are predominantly flat, non-irrigated regions comprised of complex subsurface drainage (Fausey et al., 1995; Rahman et al., 2014). However, Red River Valley soils contain greater percentages of soil organic matter and increased clay content, resulting in cation exchange capacities two to three times greater compared to the Michigan Great Lakes sugarbeet production region (Chatterjee, 2021). Although more fertile soils can benefit N-responsive cropping systems, greater organic matter content may also contribute a large unpredictable amount of mineralizable N late in the growing season, resulting in greater amino N concentrations, negatively impacting sugarbeet sucrose content. The Great Plains region spanning parts of Colorado, Montana, Nebraska, and Wyoming is comprised of lower organic matter, clay soils but lacks adequate seasonal precipitation to meet sugarbeet water demands and is routinely supplemented by irrigation (Schneekloth & Andales, 2017). Due to the inherent soil characteristics and climatology across U.S. sugarbeet production regions, management practices and in particular N management may remain region specific.

Another management consideration is the responsiveness of sugarbeet to N applications. Corn (*Zea Mays* L.), another N-responsive crop often grown in rotation with sugarbeet on similar soils, utilizes N differently than sugarbeet. In corn, N uptake is rapidly increased around the V10 growth stage (i.e., 4-6 weeks after planting) with N remobilization into the grain during later reproductive stages (Bender et al., 2013; Lauer, 2015). During this time (e.g., early August) supplying more N to corn would not serve a benefit as physiological maturity has been achieved and plants are beginning to senesce (Dharmakeerthi & Beauchamp, 2006). Sugarbeet N utilization is challenging as yield is not set at a pre-determined growth stage (e.g., corn) as sugarbeets continue to grow well into the autumn season. Therefore, sugarbeets may benefit from signs of N deficiency prior to harvest as this may signify that plant available N has remobilized to the root for bulking further diluting amino N concentration (Winter, 1998). Sugarbeet cultivars have different N-use efficiencies with some utilizing N sooner in the growing season while others may continue to hold sucrose in aboveground vegetation longer into the autumn (Ebmeyer & Hoffmann, 2021). Agronomic programs aimed at producing more consistent sucrose concentrations and tonnage may depend upon more precise N rate and cultivar pairings but will also depend upon harvest timing. In addition, the adoption of cultivar-specific N management practices will continue to require further grower education on the perception that a dark green sugarbeet field later in the season may not be a positive indication for sugar produciton.

Cultivar and Fertilizer Impacts on Root Yield and Recoverable Sucrose

In the current study, pre-planned orthogonal contrasts were planned to compare groups of treatments including 'Low N' (e.g., 5x5 N starter and 5x5 N starter + liquid K combined), 'High N' (e.g., 5x5 N starter + side-dress N and 5x5 N starter + side-dress N + liquid K combined), 'With K_2O' (e.g., 5x5 N starter + liquid K_2O and 5x5 N starter + side-dress N + liquid K combined), and 'Without K_2O' (e.g., 5x5 N starter and 5x5 N starter + side-dress N combined) within individual harvest timings. Previous research indicates a 60-70 Mg ha^{-1} sugarbeet crop removes between 70 and 120 kg K ha^{-1} (Milford et al., 2000). In the current field settings with above critical level soil K concentrations, data show the addition of liquid K did not influence root yield, recoverable sucrose, or extraction quality in either year across both high and low N environments and across contrasting varietal characteristics (Table 3.03, Table 3.04, Table 3.11). Michigan sugarbeet production largely occurs on fine-textured loam soils with high buffering capacities (14.3 – 16.4 cmol kg^{-1} in the current study) that can retain mineralized or fertilizer-supplied K on cation exchange sites and maintain water holding capacity allowing exchangeable K to remain in soil solution and readily available.

Contrasts assessing starter N-only and split-applied N rates and strategies in the current study suggest the split-applied N strategy outperformed the starter N-only strategy across both harvest timings (Table 3.11). Similar results from Purucker & Steinke (2022) showed 179 kg N

ha^{-1} generated maximum yield and recoverable sucrose during conventional harvest timing. Previous evaluations of rates between 202-247 kg N ha^{-1} demonstrated negative effects on root quality (Milford et al., 1985; Olson et al., 2018). However, N revisions may require further evaluations when considering both harvest timing and cultivar. Aggressive cultivars (e.g., C-G675) with greater tonnage and sucrose capabilities produced similar root yields with starter N only as compared to split-applied N during the 2022 October harvest (Table 3.04). However recoverable sucrose per hectare was maximized when using split-applied N. A more defensive cultivar (e.g., C-G919) required the greater N rates supplied by the split-applied N strategy across both harvest timings to maximize both root yield and recoverable sucrose. Yield differences between site years was likely influenced by wetter spring and early summer conditions in 2021 as compared to 2022, allowing for greater response to higher rates of N-fertilizer in 2021. Early harvest (i.e., mid-late August) provides an opportunity for cultivar selection to significantly impact sugarbeet root yield and quality that may be masked by time, weather conditions, or late-season disease incidence. Results support further investigation into cultivar-specific nutrient management strategies by harvest timing.

Profitability

Nitrogen fertilizer prices fluctuated from \$0.32 kg^{-1} in 2021 to \$0.55 kg^{-1} in 2022. In addition to the high cost of liquid K_2O treatments (i.e., \$1293.84 ha^{-1} in 2021 and \$1329.13 ha^{-1} in 2022) and lack of yield or quality differences, further discussions on profitability will consider the expected net return per hectare less trucking. In 2021, a cultivar by fertilizer strategy interaction affected expected net return minus trucking (Table 3.09). Split-applied nitrogen in combination with C-G675 produced the greatest return. Split-applied N combined with C-G919 also produced the greatest return but significantly less income per hectare than C-G675. Without consideration for treatment cost, liquid K application did not influence root yield or sucrose recovery and thus did not increase profitability. In 2022, C-G675 produced 12.5% greater net profitability than C-G919 when averaged across August and October harvest timings. Practitioners questioning N rates prior to being allocated early harvest hectares may still wish to split-apply N at total rates up to 179 kg N ha^{-1}. Further evaluation of N rates between 67-179 kg ha^{-1} may warrant consideration whether all N should be provided as starter 5x5 or split applied as 67kg N ha^{-1} as starter individually did not maximize August harvest yield or quality. However, the question remains as to whether or not 179 kg N ha^{-1} could be effectively utilized by the sugarbeet plant prior to a mid-to-late-August harvest timing. If allotted early harvest hectares, practitioners may wish to prioritize more aggressive cultivars as root yield and recoverable sucrose tended to be greater earlier than more defensive cultivars which may help protect conventionally harvested sugarbeets from late-season disease. Growers and practitioners alike should be aware of pre-plant soil test K concentrations as at the above critical levels tested in the current study K_2O applications did not provide any benefit.

Conclusions

In the current environments tested, cultivar selection affected root yield and recoverable sucrose per hectare of early harvested sugarbeets during both site years. Cultivars with higher tonnage and sucrose characteristics that may sacrifice some disease resistance may best be utilized during early harvest conditions when some late-season diseases are not present but increased tonnage and sucrose are needed to mitigate smaller-sized beetroots taken from production prior to autumn bulking. During 2022 conventional harvest, cultivar selection interacted with fertilizer strategy showing better N-use efficiency of C-G675 than C-G919. Cultivar selection did not significantly influence yield or sucrose recovery during 2021 conventional harvest and may be due to 25% greater season-long precipitation (i.e., less bulking and tonnage under wet soil conditions) and 6.3 cm greater September precipitation (i.e., late-season sucrose dilution) than in 2022 which not only increased disease presence likely reducing C-G675 harvest stand and quality but allowed C-G919 to bulk at a similar rate. Liquid K_2O combined with either 5x5 starter only or split-applied N strategies did not influence root yield or quality in either harvest timing or site year. In order to maximize root yield and recoverable sucrose in the current study, a split-applied N strategy totaling 179 kg N ha^{-1} was necessary during early and conventional harvest timing. However, N rates between 67 kg N ha^{-1} provided by 5x5 starter only and 179 kg N ha^{-1} split-applied should be evaluated on early harvest timing as 67 kg N ha^{-1} did not achieve maximum yield or quality.

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APPENDIX

Table 3.01. Soil physical and chemical properties and mean P, K, Ca, Mg, S soil test (0-20 cm) nutrient concentrations prior to sugarbeet planting, Richville, MI, 2021-2022.

	Soil test values†							
Year	pH	CEC	SOM	P	K	Mg	Ca	S
	g kg^{-1}	cmolc kg^{-1}	g kg^{-1}	-------------- mg kg^{-1} --------------				
2021	7.8	14.3	25	20	133	415	2100	8
2022	7.9	16.4	24	17	151	485	2400	8

†pH (1:1, soil/water); SOM soil organic matter (loss-on-ignition); P, phosphorus (Olsen sodium bicarbonate extractant); K, potassium (ammonium acetate extractable K); S, sulfur (monocalcium phosphate extraction).

Table 3.02. Mean monthly† and 30-yr‡ precipitation and temperature for the sugarbeet growing season, Richville, MI 2021-2022.

Year	Apr.	May	Jun.	Jul.	Aug.	Sept.	Total
				cm			
2021	1.8	2.9	12.5	7.3	7.8	12.8	45.1
2022	6.1	4.0	5.5	5.9	7.9	6.5	35.9
30-yr avg.	9.2	9.1	8.8	8.5	8.9	6.8	51.3
				°C			
2021	9.2	14.2	21.7	21.3	22.8	17.7	--
2022	6.6	16.5	20.2	21.7	21.1	17.2	--
30-yr avg	7.7	14.6	20.1	22.4	21.7	17.3	--

† Precipitation and temperature data were collected from MSU Enviro-weather (https://enviroweather.msu.edu/).
‡ 30-yr means were obtained from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals).

Table 3.03. Early-harvest main effects of variety and fertilizer strategy on sugarbeet yield, recoverable sucrose, sucrose concentration, and extraction purity, Richville, MI 2021-2022.

Strategy	Root Yield	Recoverable Sucrose		Sucrose	Extraction
	— Mg ha^{-1} —	— kg ha^{-1} —	— kg Mg^{-1} —	—%—	—%—
	Early Harvest 2021				
Variety					
C-G675	48.9 a*	8414 a	122 a	NA	94.6 a
C-G919	42.9 b	7269 b	122 a	NA	94.5 a
P > F	**0.07**	**0.05**	ns†	**--**	ns
Fertilizer					
5x5 N only	41.1 b	6965 b	123 a	NA	94.6 a
5x5 + Sidedress N	53.7 a	9163 a	120 a	NA	94.6 a
5x5 + Liquid K	37.8 b	6436 b	124 a	NA	94.5 a
All	51.0 a	8804 a	121 a	NA	94.7 a
P > F	**<0.001**	**<0.001**	ns	**--**	ns
	Early Harvest 2022				
Variety					
C-G675	67.1 a	8262 a	112 a	19.1 a	94.7 a
C-G919	60.2 b	7537 b	114 a	19.4 a	94.8 a
P > F	**0.002**	**0.06**	**ns**	**ns**	**ns**
Fertilizer					
5x5 N only	60.1 b	7503 a	113 ab	19.3 ab	94.6 a
5x5 + Sidedress N	67.7 a	8384 a	112 ab	19.2 ab	94.8 a
5x5 + Liquid K	60.1 b	7673 a	116 a	19.9 a	94.8 a
All	66.4 a	8035 a	110 b	18.9 b	94.7 a
P > F	**<0.001**	**ns**	**0.09**	**0.07**	**ns**
C-G675 Check¶	52.4	6753	114	19.5	95.1
C-G919 Check	45.6	5819	116	19.7	94.5

* Values in the same column followed by the same lowercase letter are not significantly different at α=0.10.

† ns = not significant at α=0.10.

¶ Non-treated control not included in statistical analysis.

Table 3.04. Conventional harvest main effects of variety and fertilizer strategy on sugarbeet yield, recoverable sucrose, sucrose concentration, and extraction purity, Richville, MI 2021-2022.

Strategy	Root Yield	Recoverable Sucrose		Sucrose	Extraction
	— Mg ha^{-1} —	— kg ha^{-1} —	— kg Mg^{-1} —	—%—	—%—
		Conventional Harvest 2021			
Variety					
C-G675	83.5 a*	13919 a	113 a	19.2 a	94.8 a
C-G919	79.8 a	13908 a	111 a	18.9 a	94.7 a
P > F	ns	ns	ns	ns	ns
Fertilizer					
5x5 N only	71.0 b	11856 b	112 a	19.0 a	94.8 a
5x5 + Sidedress N	91.4 a	15443 a	112 a	19.0 a	94.6 a
5x5 + Liquid K	68.7 b	12387 b	112 a	19.1 a	94.8 a
All	95.5 a	15967 a	112 a	19.0 a	94.8 a
P > F	**<0.001**	**<0.001**	ns	ns	ns
		Conventional Harvest 2022			
Variety					
C-G675	§	§	141 a	23.3 a	95.8 a
C-G919			138 a	23.0 a	95.8 a
P > F			**ns**	**ns**	**ns**
Fertilizer					
5x5 N only			140 ab	23.1 ab	95.8 a
5x5 + Sidedress N			140 ab	23.2 ab	95.7 a
5x5 + Liquid K			143 a	23.7 a	95.8 a
All			137 b	22.7 b	95.8 a
P > F			**0.07**	**0.05**	**ns**
C-G675 Check¶	71.6	10981	140	23.2	96.0
C-G919 Check	53.0	7901	137	22.7	95.8

*Values in the same column followed by the same lowercase letter are not significantly different at α=0.10.

§ For interactions regarding variety x fertilizer strategy, see table 3.07 for effects on root yield, and table 3.08 for effects on kg ha^{-1} recoverable sucrose.

¶ Non-treated control not included in statistical analysis.

Table 3.05. Interaction between cultivar and fertilizer strategy on sugar beet yield during conventional harvest timing, Richville, MI, 2022.

	Variety		
Fertilizer	C-G675	C-G919	***P* > *F***
	——— Mg ha^{-1} ———		
5x5 N only	89.98 a†A‡	67.23 bB	**<0.001**
5x5 + Sidedress N	92.83 aA	90.18 aA	**0.40**
5x5 + Liquid K	80.14 aB	66.40 bB	**0.03**
All	93.32 aA	92.20 aA	**0.85**
P* > *F	**0.09**	**<0.001**	

†Values followed by the same lowercase letter in the row are not significantly different at α = 0.10.
‡Values followed by the same uppercase letter in the same column are not significantly different at α = 0.10.

Table 3.06. Interaction between cultivar and fertilizer strategy on sugar beet recoverable sucrose per hectare during conventional harvest timing, Richville, MI, 2022.

	Variety		
Fertilizer	C-G675	C-G919	***P* > *F***
	——— kg ha^{-1} ———		
5x5 N only	14080 a†AB‡	10167 bB	**<0.001**
5x5 + Sidedress N	14331 aA	13849 aA	**0.56**
5x5 + Liquid K	12779 aB	10325 bB	**0.007**
All	14163 aAB	13828 aA	**0.68**
P* > *F	**0.22**	**<0.001**	

†Values followed by the same lowercase letter in the row are not significantly different at α = 0.10.
‡Values followed by the same uppercase letter in the same column are not significantly different at α = 0.10.

Table 3.07. Harvest timing, cultivar, and fertilizer strategy main effects on sugarbeet expected net return, expected net return minus trucking costs, and expected net return minus trucking and fertilizer costs, Richville, MI, 2021-2022.

Strategy	Expected gross return	Expected net return minus trucking cost	Expected net return minus trucking and fertilizer costs
	US$ ha^{-1}		
	2021		
Harvest			
Early	4366 a*	4177 a	3309 a
Conventional	4227 a	3938 a	3074 a
P > F	ns†	ns	ns
Variety			
C-G675	§	§	§
C-G919			
P > F			
Fertilizer			
5x5 N only			
5x5 + Sidedress N			
5x5 + Liquid K			
All			
P > F			
	2022		
Harvest			
Early	5941 b	5569 b	4527 b
Conventional	6873 a	6526 a	5484 a
P > F	**<0.001**	**<0.001**	**<0.001**
Variety			
C-G675	6782 a	6402 a	5360 a
C-G919	6032 b	5693 b	4651 b
P > F	**0.002**	**0.002**	**0.002**
Fertilizer			
5x5 N only	6040 b	5702 b	5516 a
5x5 + Sidedress N	6895 a	6508 a	5963 a
5x5 + Liquid K	5954 b	5626 b	4048 b
All	6739 a	6353 a	4459 b
P > F	**<0.001**	**<0.001**	**<0.001**
C-G675 Check¶	4662	4405	4405
C-G919 Check	3644	3441	3441

* Means in the same column following the same lowercase letter are not significantly different at α=0.10.

† ns = not significant at α=0.10.

§ For interaction of variety and fertilizer strategy, see table 3.10 for expected net return, table 3.11 for return minus trucking cost, and table 3.12 for return minus trucking and fertilizer costs.

¶ Non-treated control not included in statistical analysis.

Table 3.08. Interaction between cultivar and fertilizer strategy across both harvest timings on sugarbeet expected gross return, Richville, MI, 2021.

	Variety		
Fertilizer	C-G675	C-G919	***P > F***
	US$ ha^{-1}		
5x5 N only	3726 a†B‡	3944 aBC	**0.46**
5x5 + Sidedress N	5207 aA	4544 bA	**0.04**
5x5 + Liquid K	3907 aB	3459 aC	**0.18**
All	5300 aA	4290 bAB	**0.002**
P > F	**<0.001**	**0.008**	

†Values followed by the same lowercase letter in the row are not significantly different at α = 0.10.
‡Values followed by the same uppercase letter in the same column are not significantly different at α = 0.10.

Table 3.09. Interaction between cultivar and fertilizer strategy across both harvest timings on sugarbeet expected net return minus trucking costs, Richville, MI, 2021.

	Variety		
Fertilizer	C-G675	C-G919	***P > F***
	US$ ha^{-1}		
5x5 N only	3504 a†B‡	3704 aBC	**0.51**
5x5 + Sidedress N	4890 aA	4292 bA	**0.07**
5x5 + Liquid K	3674 aB	3408 aC	**0.39**
All	4977 aA	4028 bAB	**0.003**
P > F	**<.0001**	**0.04**	

†Values followed by the same lowercase letter in the row are not significantly different at α = 0.10.
‡Values followed by the same uppercase letter in the same column are not significantly different at α = 0.10.

Table 3.10. Interaction between cultivar and fertilizer strategy across both harvest timings on sugarbeet expected net return minus trucking and fertilizer costs, Richville, MI, 2021.

	Variety		
Fertilizer	C-G675	C-G919	***P > F***
	US$ ha^{-1}		
5x5 N only	3395 a†B‡	3595 aA	**0.47**
5x5 + Sidedress N	4584 aA	4023 bA	**0.06**
5x5 + Liquid K	2243 aC	1979 aC	**0.35**
All	3348 aB	2676 bB	**0.03**
P > F	**<0.001**	**<0.001**	

†Values followed by the same lowercase letter in the row are not significantly different at α = 0.10.
‡Values followed by the same uppercase letter in the same column are not significantly different at α = 0.10.

Table 3.11. Orthogonal contrasts assessing the addition of liquid K_2O (K_2O vs. no K_2O) and N-management (starter N vs. split-applied N), across both early and conventional harvest timings, Richville, MI 2021-2022.

Strategy	Root Yield	Recoverable Sucrose		Sucrose	Extraction
	— $Mg\ ha^{-1}$ —	— $kg\ ha^{-1}$ —	— $kg\ Mg^{-1}$ —	—%—	—%—
			Early Harvest 2021		
With K_2O	44.4 a*	7621 a	122 a	NA	94.6 a
Without K_2O	47.4 a	8065 a	123 a	NA	94.6 a
P > F	ns†	ns	ns	--	ns
Starter N only	39.5 b	6701 b	136 a	NA	94.5 a
Split-applied N	52.3 a	8964 a	133 b	NA	94.7 a
P > F	**<0.001**	**<0.001**	**0.07**	--	ns
			Early Harvest 2022		
With K_2O	63.3 a	7855 a	125 a	19.4 a	94.8 a
Without K_2O	64.0 a	7943 a	124 a	19.2 a	94.7 a
P > F	ns	ns	ns	ns	ns
Starter N only	60.1 b	7588 b	126 a	19.6 a	94.7 a
Split-applied N	67.1 a	8210 a	123 b	19.0 b	94.8 a
P > F	**<0.001**	**0.03**	**0.04**	**0.03**	ns
			Conventional Harvest 2021		
With K_2O	82.2 a	14178 a	124 a	19.0 a	94.8 a
Without K_2O	81.1 a	13650 a	124 a	19.0 a	94.7 a
P > F	ns	ns	ns	ns	ns
Starter N only	72.6 b	12122 b	124 a	19.1 a	94.8 a
Split-applied N	90.8 a	15705 a	124 a	19.0 a	94.7 a
P > F	**0.002**	**<0.001**	ns	ns	ns
			Conventional Harvest 2022		
With K_2O	83.0 a	12774 a	154 a	23.2 a	95.8 a
Without K_2O	85.7 a	13107 a	154 a	23.1 a	95.8 a
P > F	ns	ns	ns	ns	ns
Starter N only	76.0 b	11838 b	156 a	23.4 a	95.8 a
Split-applied N	92.2 a	14043 a	152 b	23.0 b	95.8 a
P > F	**<0.001**	**<0.001**	**0.06**	**0.05**	ns

* Values in the same column followed by the same lowercase letter are not significantly different at α=0.10.
† ns = not significant at α=0.1.