EFFECTS OF NUTRIENT MANAGEMENT STRATEGIES ON DRY MATTER AND GRAIN YIELD OF SOYBEAN AND DRY BEAN CROPPING SYSTEMS

By

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ABSTRACT

EFFECTS OF NUTRIENT MANAGEMENT STRATEGIES ON DRY MATTER AND GRAIN YIELD OF SOYBEAN AND DRY BEAN CROPPING SYSTEMS

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Increases in soybean (*Glycine max* L. Merr.) grain yield can be partially attributed to greater total dry matter (TDM) accumulation, but the relationship between dry matter (DM) accumulation and nutrient uptake across irrigated and non-irrigated conditions remains uncertain. Two multi-year trials investigated soybean dry matter and nutrient accumulation and partitioning, grain yield, and net economic return across multiple seeding rates and fertilizer strategies. The 148,000 seeds ha^{-1} rate significantly decreased yield in two of four site-years but no differences occurred at the remaining two site-years. Fertilizer strategies did not interact with seeding rate to influence grain yield across all site-years. When contemplating fertilizer application strategies, soil test values should still be the first factor considered.

Greater grain yield potential from improved dry bean (*Phaseolus vulgaris* L.) varieties coupled with potential decreases in soil sulfur (S) supply may have affected the likelihood of a grain yield response to nitrogen (N) and sulfur application. Three multi-year trials were established in Michigan to evaluate nitrogen rate, sulfur rate, and sulfur source on dry bean growth and grain yield. Nitrogen and S application including S source did not improve grain yield or interact with variety to affect grain yield across site-years. Other factors including plant nodulation, biomass, and residual nitrate after harvest were affected by N or S treatments. Nutrient application, especially N, may still be required but in nominal quantities to account for the variable June planting conditions of this shorter-season cropping system. Sulfur applications may be better suited for more N-responsive crops within the dry bean cropping rotation.

Dedicated to my family, friends, and colleagues who extended their love, assistance, and advice along the way.

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CHAPTER 1

LITERATURE REVIEW

Soybean

Global and Domestic Soybean Production

Globally soybean is currently a leading source of protein and oil for human food, animal feed, and industrial products (Wilson, 2008). Soybean meal produced in the crushing and oil extraction process accounts for the 65% of protein feed worldwide (Balboa et al., 2018). In 2017, the United States was the second largest exporter producing approximately 33% of world soybean production and exporting more than 59 million metric tons (USDA-FAS, 2017). In conjunction with the United States, Brazil, Argentina, China, India, Paraguay, and Canada produced approximately 94% of the world's soybeans in 2017 (USDA-FAS, 2017).

Soybean was first introduced within the United States as a forage crop in 1765 by Samuel Bowen (Hymowitz, 1990). However, it was until after World War II when the manufacturing of oil, meal, and food products from soybean increased the demand for a larger grain production market (Morse et al., 1950). During this same period, the United States surpassed China and later countries of the Orient in soybean production. (Hymowitz and Shurtleff, 2005).

Between 1924 and 2018, average grain yield within the United States increased 324%. These on-farm yield gains are partially contributed to the adoption of new cultivars, improved agronomical practices, interactions between new cultivars and improved agronomical practices, and increased atmospheric CO_2 levels (Long et al., 2006; Ziska and Bunce, 2007; Rowntree et al., 2013; Rowntree et al., 2014; Specht et al., 2014).

Seeding Rate and Plant Density

Producers in the U.S. are forced to rethink optimum seeding rates for maximum yield and economic return due to the high cost of soybean seed (Chen and Wiatrak, 2011). Lee et al. (2008) reported seeding rates may be reduced below current recommendations (i.e., 300,000 to 516,000 seeds ha^{-1}) without sacrificing yield. Elgi (1988b) found plant densities may be higher than those required to achieve 95% insolation interception at the growth stage R5 to maximize yields of indeterminate varieties. Harder et al. (2007) observed increasing seeding rate from approximately 300,000 plants ha^{-1} to 445,000 plants ha^{-1} did not result in quicker canopy closer, reduced weed emergence, or greater soybean yield and gross margins. In New York, a low seeding rate of 358,000 seeds ha^{-1} yielded similarly with the recommended 469,000 seeds ha^{-1} rate by producing additional side branches, vegetative biomass, pods, and seeds per plant (Cox et al., 2010). Koger (2009) also found low final plant populations produce optimum yields by compensating and increasing the number of fruiting branches, pods, and seeds per plant. However, high seeding rates provide protection against in-season stresses such as inadequate seedling emergence due to poor seed quality or unsuitable planting conditions but also increase the risk for white mold (Lee et al., 2008; Carpenter, 2020).

When moisture is non-limiting, plant spacing has no effect on soybean yield (Alessi and Power, 1982; Board 2000). However, under extreme drought situations increased plant competition may reduce late-season water availability and ultimately yield due to increased early-season water use compared to decreased inter-plant competition (Alessi and Power, 1982).

Nutrient Uptake, Partitioning and Remobilization

Nitrogen Uptake: Gaspar et al. (2017a) termed the first 20 day after emergence as a lag phase for N uptake due to N uptake rates < 1 kg ha^{-1} d^{-1}. However, N uptake rates at 30 days after emergence (V4) is greater for high yield levels (5500 kg ha^{-1}) compared to average (4500 kg ha^{-1}), and low yield levels (3500 kg ha^{-1}) (Gaspar et al., 2017a). Total season-long N uptake by R1 for low, average, and high yield levels were reported at 14, 13, and 12%, respectively by Gaspar et al. (2017a). Previous research observed peak N uptake at R4 (Bender et al., 2017; Gaspar et al., 2017a). Bender et al (2015) found N uptake is evenly distributed between vegetative and seed-filling growth phases but Gaspar et al. (2017a) determined higher yield levels rely more heavily on N uptake from the soil after R5.5 than average and low yield levels. Moreover, Gaspar et al. (2017a) found total N uptake is greater for high yield levels compared to average and low yield levels, which is contributed from a shorter duration in the lag phase of early season N uptake, a higher peak N uptake rate, an extended peak uptake period, and greater late-season uptake amounts and rates.

Nitrogen Partitioning: Past reports have indicated leaf tissue acts as a temporary N storage organ (Hanway and Weber, 1971a; Shibles and Sundberg, 1998; Sinclair, 1998). Gaspar et al. (2017a) suggest DM partitioning displays little influence on N partitioning. According to Gaspar et al. (2017a), N partitioned to leaves, seeds, stems, pods, and petioles across multiple yield levels at R5.5 was 43.7, 18.0, 16.2, 13.9, and 5.4%, respectively. Bender et al. (2015) reported over half of seed N accumulation occurs after the onset of seed-filling, indicating the importance of soil N resources to prevent yield losses. From what N is remobilized to the seed, 65% comes from leaf N contents and 32% comes from stem N contents (Bender et al., 2015). Compared to older varieties, modern varieties can remobilize and uptake more N past R5.5 to meet seed N demands due to increased yield (Gaspar et al., 2017a).

Nitrogen Removal: On a dry matter basis, Salvagiotti et al. (2008) observed a seed N concentration of 6.34%. At a yield level of 3480 kg ha^{-1}, Bender et al. (2015) reported a nitrogen harvest index (NHI) of 73% while Hanway and Weber (1971) reported a NHI of 68% at a 2855 kg ha^{-1} yield level. Despite a significant interaction between environment and seed yield, Gaspar et al. (2017a) found NHI increased with seed yield for low (82.1%), average (83.3%) and high (84.1%) yield levels. Compared with the results from Salvagiotti et al. (2008), Gaspar et al. (2017a) observed current production realities incorporating modern soybean varieties and farm management practices combined with a greater NHI support a lower total N requirement across yield levels.

Phosphorus Uptake: Compared to low (3500 kg ha^{-1}) and average (4500 kg ha^{-1}) yield levels, the lag phase of early season P uptake is shorter for high yield levels (5500 kg ha^{-1}) (Gaspar et al., 2017b). In Wisconsin and Minnesota, early season P uptake acquired by R1 accounted for 15% (3.6 kg ha^{-1}), 13% (3.9 kg ha^{-1}), and 11% (4.1 kg ha^{-1}) of total season-long P uptake for low, average, and high yield levels, respectively (Gaspar et al., 2017b). Phosphorus uptake reaches ~50% by R4 once reproductive growth is initiated (Hanaway and Weber, 1971; Bender et al., 2015). Bender et al. (2015) found peak P uptake rates were attained at R4 while Gaspar et al. (2017b) reported R3. Peak uptakes rates were reported as .34 kg P ha^{-1} d^{-1} by Hanway and Weber (1971), .40 kg P ha^{-1} d^{-1} by Bender et al. (2015), and .42, .48, and .56 kg P ha^{-1} d^{-1} for low, average, and high yield levels, respectively, by Gaspar et al. (2017b). Total P uptake for high (36.6 kg P ha^{-1}), average (29.3 kg P ha^{-1}), and low (24.4 kg P ha^{-1}) yield levels was reported by

Gaspar et al. (2017b). Similar to N, P uptake is generally evenly distributed between vegetative and seed-filling growth phases (Bender et al., 2015; Gaspar et al., 2017b).

Phosphorus Partitioning: Gaspar et al. (2017b) found P was partitioned into leaves (28.6%), stems (27.6%), pods (16.0%), seeds (15.4%), petioles (10.8%), and fallen leaves and petioles (<2%) at R5.5. Hanway and Weber (1971) reported P remobilization at 56% while Bender et al. (2015) reported P remobilization at 69%. New varieties and production practices compared to old varieties and production practices have resulted in greater remobilization and uptake of P past R5.5 (Gaspar et al., 2017b). Approximate seed P contributions between vegetative remobilization and continued uptake past R5.5 are approximately 50% (Bender et al., 2015 Gaspar et al., 2017b).

Phosphorus Removal: Since the 1930's, phosphorus harvest index (PHI) has increased from 68 to 80% in current soybean varieties (Borst and Thatcher, 1931). Seed PHI ranges from 72% to 82% on a DM basis (Hanway and Weber 1971; Bender et al., 2015; Gaspar et al., 2017b). According to Gaspar et al. (2017b), 23.8 kg P ha^{-1} would be removed with the seed at a yield of 4421 kg ha^{-1}. Phosphorus HI is reported to vary due to environment but not yield (Gaspar et al. 2017b).

Potassium Uptake: Instances of luxury K uptake have been observed when soil K supply was excessively high (Clover and Mallarino, 2013). Potassium uptake at R1 was observed at 26% (33.1 kg K ha^{-1}), 22% (34.1 kg K ha^{-1}), and 18% (34.4 kg K ha^{-1}) of total season-long K at low (3000 kg ha^{-1}), average (3500 kg ha^{-1}), and high yield (5500 kg ha^{-1}) levels, respectively (Gaspar et al. 2017b). Farmaha et al. (2012), however, found the K uptake rate at R1 to be 20 kg K ha^{-1}. Potassium uptake nears completion by R5.5 for low yield levels whereas average and high yield levels accrue 97% and 91% of total season-long K by R5.5, respectively (Gaspar et al., 2017b). If growing conditions after R5.5 are not suitable for average yields, luxury K accumulation will occur because a majority of total season-long K uptake is completed by R5.5 (Gaspar et al., 2017b). Peak uptake rates range from 1.5 kg K $ha^{-1}d^{-1}$ to 2.5 kg K ha^{-1} d^{-1} and occur shortly after R2 (Hanway and Weber, 1971; Gaspar et al., 2017b).

Potassium Partitioning: Across multiple yield levels Gaspar et al. (2017b) found K was distributed equally to stems (31%), petioles (26%) and leaves (43%) at R1. Potassium remobilization at R5.5 ranges from 36% to 46.3% (Hanway and Weber, 1971; Bender et al., 2015; Gaspar et al., 2017b). Although continued K uptake past R5.5 is partitioned to the seed, K is also partitioned to the pod (Gaspar et al., 2017). However, seed K demands at multiple yield levels is mostly supplied by vegetative K remobilization (Hanway and Weber, 1971; Bender et al., 2015; Gaspar et al., 2017b).

Potassium Removal: High and low STK levels have been shown to produce variable seed K concentrations (Parvej et al., 2016). Due to the relatively low amount of vegetative K that is remobilized to the seed, potassium harvest index (KHI) is also substantially low because a majority of K uptake remains in stems, petioles, leaves, and pods at maturity (Hanway and Weber, 1971; Bender et al., 2015; Gaspar et al., 2017b). Potassium HI ranges from 48.9% to 62% at maturity as reported by Hanway and Weber (1971), Bender et al. (2015), and Gaspar et al. (2017b). Due to > 50% of total K uptake potentially in the stover at harvest, the estimated amount of K removed in the stover may increase soil K depletion (Fixen et al., 2010).

Sulfur Uptake: Gaspar et al (2018) found total S uptake is not dependent on environment or variety but is dependent on yield. Gaspar et al. (2018) reported a greater reliance on late season S uptake for higher yields levels (5500 kg ha^{-1}) than average (4500 kg ha^{-1}) and low (3500 kg ha^{-1}) yield levels. Peak S uptake occurs between R3 and R4 (Bender et al., 2015; Gaspar et al., 2018). Peak uptake rates vary between low (.26 kg S ha^{-1} d^{-1}), average (.28 kg S ha^{-1} d^{-1}), and high (.33 kg S ha^{-1} d^{-1}) yield levels (Gaspar et al., 2018). After R5.5, Bender et al. (2015) and Gaspar et al. (2018) found S uptake ranged from 24.9% to 32.2% of season-long total S uptake.

Sulfur Remobilization: When pooled across all yield levels at R5.5, 33.4, 28.8, 11.6, 12.9, and 10.2% of S was partitioned to the leaves, stems, seeds, pods, and petioles, respectively, while the remainder was lost to fallen leaves and petioles (Gaspar et al., 2018). On a relative basis, Bender et al. (2015) and Gasper et al. (2018) reported the total amount of vegetative S remobilized ranged from 40% to 50.1%. Seed S acquired during seed-fill from the soil is directly moved to the seed (Naeve and Shibles, 2005). The percentage of seed S demands met with continued uptake past R5.5 for low, average, and high yield levels is 49.9, 53.5, and 58% respectively (Gaspar et al., 2018).

Sulfur Removal: Sulfur harvest index (SHI) ranges from approximately 61 to 69% according to Bender et al. (2015), Gaspar et al. (2018), and Sexton et al. (1998). Gaspar et al. (2018) reported 10.2 kg S ha^{-1}, 12.3 kg S ha^{-1}, and 15.1 kg S ha^{-1} being removed with the seed at low (3500 kg ha^{-1}), average (4500 kg ha^{-1}), and high yield levels (5500 kg ha^{-1}). Greater S removal with the seed as yield increases (.0003 kg S kg $grain^{-1}$) is mostly met by uptake from the soil after R5.5 (Gaspar et al., 2018).

Zinc Uptake: At an average yield of 4421 kg ha^{-1}, total Zn uptake is 22 kg ha^{-1} (Gaspar et al. (2018). Bender at al. (2015) found the peak S uptake rate of 3.57 to 3.99 g ha^{-1} d^{-1} occurs at R4. Approximately 53% of seed Zn is met through continued uptake past R5 (Gaspar et al. 2018), and 335 g ha^{-1} is required to produce approximately 3500 and 9500 kg ha^{-1} of grain and total biomass, respectively (Bender et al, 2015).

Zinc Remobilization: Zinc uptake prior to R1 or approximately 38 DAE is less than 17% of total season-long Zn uptake (Gasper et al., 2018). At R5.5, large portions of Zn (46%) is held in leaf tissue (Gaspar et al. 2018). On a per kg basis, Bender et al. (2015) reported grain Zn concentration at.40.2 mg. At an average yield level of 4421 kg ha^{-1}, Gaspar et al. (2018) reported zinc harvest index (ZHI) at 68.7% while Bender et al. (2015) reported ZHI at 44%.

Zinc Removal: At an average yield of 4421 kg ha^{-1}, 16 kg Zn ha^{-1} is being removed with the seed at harvest (Gaspar et al. 2018). Due to such a small amount of Zn and other micronutrients being removed with the grain (< .18 kg ha^{-1}), there is little or no need to fertilize for micronutrients as often you would fertilize with macronutrients (Gaspar et al., 2018). However, Bender et al. (2015) reported 195 g Zn ha^{-1} would be removed if the non-grain portion of the plant was not returned to the soil.

Dry Matter Accumulation, Partitioning, and Removal

Seed yields over the past century can partially be contributed to greater total plant DM through better management and improved plant genetics (Frederick et al., 1991; Rincker et al., 2014). In modern soybean varieties, each kilogram increase in yield translates to 1.45 kg increase in total dry matter accumulation (Gaspar et al., 2017a). Hanway and Weber (1971) found an average total dry matter accumulation of 9680 kg ha^{-1} for a yield level of 2983 kg ha^{-1} with a peak accumulation rate of 88 to 149 kg ha^{-1} d^{-1}. However, Bender et al. (2015) reported an average DM accumulation of 9775 kg ha^{-1} for a yield of 3480 kg ha^{-1} with a peak accumulation rate of 162 kg ha^{-1} d^{-1} and Carpenter and Board (1997) found an accumulation rate of 60 kg ha^{-1}

d^{-1} at R1 and a peak uptake rate of 180 kg ha^{-1} d^{-1} at a 3600 kg ha^{-1} yield level. Although yield increase as total DM increases, environmental factors affecting crop growth rate may also increase or decrease total DM accumulation (Muchow, 1985).

Gaspar et al. (2017b) reported early season DM accumulation was mostly partitioned into leaf tissue until R1 when an increased amount of DM was transferred to stems, petioles and into pods at R3.5 and seeds at R4.5. Most DM is partitioned into the stems, followed by leaves, pods, petioles, seeds, and the rest as fallen leaves and petioles (Hanway and Weber, 1971; Bender et al., 2015; Gaspar et al., 2017a). Continued partitioning of DM to stems and pods occurs until R6.5 and remobilization of all vegetative DM at the peak DM accumulation is lower for high yield levels (5500 kg ha^{-1}) than average (4500 kg ha^{-1}) and low (3500 kg ha^{-1}) yield levels (Gaspar et al., 2017a). This could theoretically lead to an extended duration of photosynthetic supply to the seed (Imsande, 1989). Harvest index (HI) differs for low (42.8%), average (44.2%), and high (45.2%) yield levels as reported by Gaspar et al. (2017a), suggesting greater total DM potentially does not always translate to greater grain yield.

Nutrient Application

Nitrogen: A growing soybean crop needs nitrogen from three different sources: N mineralization, synthetic N fertilizer, and biological N fixation (Barker and Sawyer, 2005; Salvagiotti et al., 2008). Biological N fixation can provide up to 50-60% of soybean’s total N requirement (Salvagiotti et al., 2008; Tamagno et al., 2017). Previous research reported N application reduces the number of nodules per plant and may sometimes reduce yield (Streeter and Wong, 1988; Hankinson et al., 2015). Although N application may reduce nodulation, certain forms of N such as nitrate are more sensitive to nodules than ammonium and urea

(Ralston and Imsande, 1983; Salsbury et al., 1986). Previous research has shown that N response in soybean is more likely under high yield conditions when N fixation and N mineralization are unable to provide sufficient N to meet crop demand (Salvagiotti et al., 2008). deMooy et al. (1973) found hot and dry conditions increases the likelihood of a grain yield increase to N application while adequate soil moisture and rainfall decreases the likelihood of a grain yield increase to N application. Slaton et al. (2013) observed N applied early in the growing season with P and K did not provide a yield benefit above what was responsive to P and K. However, in Minnesota, Schmitt reported N application increased grain yield at 9 of 13 site-years.

Phosphorus: Phosphorus is important in crop production because it supports respiration, root growth, crop maturity, and drought tolerance (Bundy et al., 2005; Schlegel and Grant, 2006; Havlin et al., 2014). Under a short growing season and when soils are cool, starter P fertilizer has the potential to increase early-season vegetative growth and grain yield (Vitosh et al., 1995; Starling et al., 1998; Taylor et al., 2005; Elgi and Cornelius, 2009). However, under sufficient P soil concentrations, Purucker and Steinke (2020) did not contribute increased V4DM from a N, P, S, and Zn starter fertilizer to the P component. Sutradhar et al. (2017) found P applications at soil test phosphorus (STP) levels greater than 8 mg kg^{-1} increased grain yield. In addition, banding P with the planter in soils with low STP levels increases P uptake and grain yield compared to broadcasted P (Borges and Mallarino, 2000). Hairston et al. (1990) found deep injecting (15-cm depth) P fertilizer into soils with low STP levels increased the likelihood of a grain yield response in comparison to broadcasting P. Across all site-years, however, Hankinson et al. (2015) found P applied 2 inches below and 2 inches to the side of the seed at planting (i.e., starter fertilizer) did not increase grain yield when STP levels were greater than 15 ppm. Bharati et al. (1986) reported lodging was significantly increased by P application.

Potassium: Potassium is essential for crop growth and physiological functions, including the regulation of water and gas exchange, protein synthesis, enzyme activation, photosynthesis, and carbohydrate translocation (Marschner, 1998). Under K deficient conditions, plants may experience a reduction in plant growth, decreased drought resistance, weak stems, and greater susceptibility to disease (Sinclair, 1993, Mills and Jones, 1996). Potassium exists in most soils in the water-soluble form, readily exchangeable, and slowly exchangeable forms. However, most of the K in the soils is in the slowly exchangeable form while K uptake by the plant is mostly from the soluble and readily exchangeable forms (Hanway et al., 1985). In-season K applications can provide additional K during peak soybean uptake (Bender et al., 2015, Gaspar et al., 2017b) but yield responses depend on soil test K (STK) levels and environmental conditions (Haq and Mallarino, 2000; Nelson et al., 2005). Annual K fertilization rates that increase STK levels are desirable in low testing soils because they increase profits (Mallarino et al., 1991). Low soil test K levels may encourage K recycling in plant residues and extraction of K below the depth sampled and its later release on the surface soil (Mallarino et al., 1991). Moisture films around soil particles promotes diffusion and K uptake by the plant. Oliver and Barber (1966) estimated that 88 to 96% of K uptake reaches the roots by diffusion. Applied K should be placed where the soil will be moist and roots will be active if it’s to be utilized (Hanway et al., 1985). In a study conducted by Nelson et al. (2005), soybean yield was higher when K was soil applied compared to foliar applied. The vast majority of K uptake from K fertilization remained in the plant with no increase in yield or grain K (Oltmans and Mallarino, 2014). Potassium application increased soybean yield at 16 site-years when the concentration of K in the was soil was at or less than 173 mg K kg^{-1} (Clover and Mallarino, 2013). However, Quinn and Steinke (2019) and Purucker and Steinke found the application of potassium thiosulfate and muriate of potash (MOP), respectively, did not increase soybean yield when soil test K concentrations were above critical across site-years. Additionally. Sale and Cambell (1986) suggest applications of K to correct late season deficiencies are of little use.

Sulfur: Sulfur aids in amino acid synthesis increases resistance to cold temperatures and promotes soybean nodulation (Coleman, 1966). Results from Gutierrez Boem et al. (2007) suggest moderate S deficiency may reduce yield by affecting crop growth rate during the seed filling period due to sulfate mobility in the soil. Since the passage of The Clean Air Act of 1970, a significant reduction in atmospheric deposition of S-containing compounds on agriculture land has occurred (EPA, 2001). Kaiser et al. (2013) found soybean response to sulfur depends on the location, SOM, crop rotation, and S mineralization. Kaiser et al. (2013) also reported a response to S when SOM was less than 2%. In Michigan soil test S sufficiency ranges are not recommended due to SO_4-S variability (Vitosh et al., 1995; Warncke et al., 2009). Tissue S and SOM are better predictors of a soybean S response rather than soil S (Hitsuda et al., 2008; Kaiser and Kim, 2013). Hitsuda et al. (2008) suggest S levels in the seed are a good indicator of the suflur fertility status of a field and may determine if sulfur fertilization is necessary before a subsequent soybean crop. Ham et al. 1975 found S fertilization does not increase total S percentage and S containing amino acids of the seed. In Ohio and Michigan under sufficient tissue S concentrations, Bluck et al. (2015) and Quinn and Steinke (2020), respectively, did not observe a grain yield response to S fertilization.

Zinc: Zinc deficiency can occur on a wide variety of soils with a high amount of silica and $CaCO_3$ (Moraghan and Mascagni, 1991; Sutradhar et al., 2016). In Minnesota the application of Zn increased soybean trifoliate concentration but it did not increase soybean grain yield (Sutradhar et al., 2017). Soil tests do not predict a soybean grain yield response to Zn and there are no relationships between trifolliate Zn concentration and grain yield or to the soil test (Sutradhar et al., 2017). Research from Iowa showed that foliar appield Zinc increased Zn concentration in the trifoliate and seed but did not increase grain yield (Enderson et al., 2015). Across 18 sites in Iowa a fertilizer mixture that contained Zn sprayed at the V5 growth stage did not increase yield (Mallarino et al., 2001). However, Rose et al. (1981) found foliar applied Zn before flowering increased grain yield 13 to 208% at 75% of the locations.

Dry Bean

Global and Domestic Dry Bean Production

Dry bean is a valuable legume crop and one of the leading sources of dietary protein worldwide. In 2019 the United States produced 1,165,416 tons of dry edible bean, of which Michigan accounted for 18% of total production (USDA-NASS, 2019). Michigan is the largest producer of black bean, navy bean and small red bean in the United States (USDA-NASS, 2020). Furthermore, Michigan plants additional market classes of dry bean including cranberry, dark red kidney, light red kidney, white kidney, pinto, and adzuki.

Nitrogen

Compared with other legumes such as soybean, the ability of dry bean to fix N is relatively low, therefore mineral N and N fertilizer are essential to satisfy plant N demand (Fageria et al., 2014). The limited N fixation capacity of dry bean is thought to be the product of a low N requirement and presence of N assimilation traits favoring mineral N uptake rather than N fixation (George and Singleton, 1992). The contributions of symbiotic nitrogen fixation (SNF) and mineral N sources to total N accumulation are determined by the N requirement of dry bean and the mineral supply of N where if mineral N uptake is less than the N requirement, N fixation is potentially promoted (George and Singleton, 1992). However, environmental factors such as precipitation and temperature may impact the rate at which N mineralization and SNF occurs (Harper and Gibson, 1984; Andrews et al., 2005). For example, hot or cold weather and periods of soil water saturation can lead to the abortion or sloughing off of nodules, resulting in a greater demand for N uptake from other N sources (Liebman et al., 1995). In favorable environmental conditions, N availability may increase due to greater N mineralization from crop residues and organic matter, thus promoting higher yields (Franzen, 2017). Consequently, N fixation and mineral N uptake without the addition of N fertilizer may fail to support the N needs of a high yielding crop (Piha and Munns, 1987). Previous research has demonstrated dry bean may vary in response to N fertilizer addition across genotypes in part due to differences in N use efficiency (Fageria et al., 2013).

Symbiotic N fixation begins once the colonization of the rhizosphere and the infection of the legume roots by rhizobia leads to nodule formation (Hardy et al., 1971). However, the capability of N fixation to support legume N supply may be influenced by environmental factors such as extreme pH, low soil temperature, drought, salinity, and soil deficiencies in P, K, and S

(Kumarasinghe et al., 1992; Faghire et al., 2011; Divito and Sandras, 2014). Due to the highly volatile nature of SNF in response to environmental conditions, N management in dry bean production poses a difficult challenge (Farid et al., 2015). Although most modern dry bean varieties were developed for high yield potential in N-rich soils, previous research has demonstrated high soil N levels negatively correlate with SNF (Salvagiotti et al., 2008). In a recent study evaluating 16 dry bean genotypes from different market classes under four different N treatments [not inoculated low N (27 lb N/acre) and high N (89 lb N/acre) and two rhizobia strains], Akter et al. (2018) verified a high dose of N fertilizer may suppress N fixation. Furthermore, Argraw and Akuma (2015) found a decrease in nodule number and weight with increased rates of N fertilizer in dry bean without inoculation. In addition to environmental factors and soil N level, nodulation can also be influenced by genotype (Fageria et al., 2013), where increased nodule number correlates with greater N fixation (Pereira et al., 1993). As a result, this discrepancy in nodulation (i.e., N fixing capabilities) across market classes and varieties may alter N management, especially in regions where dry bean producers grow multiple market classes.

Dry bean needs 100 to 125 lb of N/acre for maximum yield in conjunction with N fixed by nodules on the plant (Hergert et al., 2013). To ensure high grain yield potential, Warncke et al. (2009) suggests applying 60 lb N/acre for when colored beans are grown under irrigation or if beans are planted in narrow rows (less than 23-inches), and 40 lb N/acre for all other beans under less intensive management systems. However, high rates of N applied pre-plant and incorporated has the potential to reduce plant stand due to saltation, but rainfall can mitigate risk for salt injury by reducing the concentration of N in the germination zone (Steinke and Bauer, 2017). In Wyoming, N rates of 0, 40, 80, 120, and 153 lb N/acre produced a curvilinear yield response in one of three years and a linear response in the range of the rates used in two of three years (Blaylock., 1995). Moraghan et al. (1991) found the application of N fertilizer beyond 50 lb N/acre on navy bean did not significantly increase grain yield at one of four locations, where N fertilizer had either no impact or a decrease in grain yield at the remaining locations. Moreover, past research conducted by Edje et al. (1975) determined grain yield was greatest up to 71 lb N/acre across all site-years. Chekanai et al. (2018) observed greater pods per plant, number of seeds per pod, and grain yield when 36 lb N/acre was applied pre-plant compared to applying no N. Although previous research has shown the application of N at pre-plant leads to higher dry bean yields compared to applying N fertilizer after crop emergence (Kluthcouski et al., 2005), Sorrato et al. (2014) found grain yield was maximized at a V3 side-dressed N rate of 75 and 107 lb N/acre for a newly implemented no-tillage system and an established no-tillage system, respectively, in addition to 54 lb N/acre applied at pre-plant. However, without a split N application strategy, Eckert et al. (2011) determined 100 lb N/acre side-dressed at V3 did not significantly increase grain yield of three pinto bean cultivars.

Previous research has documented greater initial plant growth of dry bean when there was a high availability of nutrients during the early stages of development (Kluthcouski et al., 2005). Additionally, Soratto et al. (2014) found the application of 54 lb N/acre before planting increased initial plant growth and decreased plant mortality during early vegetative stages and concluded N fertilizer was important for the acceptable establishment of dry bean. Karasu et al. (2011) reported increased doses of N ranging from 27 to 107 lb N/acre on dwarf dry bean cultivars resulted in greater plant height and more plant branches compared to applying no N, but there were no significant differences between N rates greater than 27 lb N/acre. Despite the potential benefit of increased grain yield and biomass production, the addition of N fertilizer may also delay dry bean flowering and maturity (Reinprecht et al., 2020). In a study evaluating the application of 100 lb N/acre at V3, Eckert et al. (2011) observed a one-day delay in both the days to flowering and maturity. Furthermore, the over application of N fertilizer beyond a grain yield response may promote a microclimate within the bean canopy suitable for pathogen development, especially white mold (*Phaseolus vulgaris* L.). Outside of climatic conditions during canopy closure, which generally occurs during the flowering growth stages (R1-R3), N fertilizer may increase moisture within the canopy by stimulating foliage growth, thus decreasing air flow and lack of soil water evaporation (Miklas et al., 2013). This disease caused by the fungal pathogen *Sclerotinia sclerotiorum*, can limit yield potential and reduce seed and pod quality across many major bean producing regions (Singh and Schwartz, 2010). Apart from N fertilizer application, cultural practices such as row spacing, seeding rate, irrigation, and variety selection may also influence white mold infection.

Nitrogen is the most frequently lacking and highest required nutrient in dry bean production (Fageria et al., 2014). To obtain maximum plant growth and yield, dry bean requires supplemental N fertilizer due to relatively poor N fixation. However, most plants are unable to utilize most of what N fertilizer is applied, thus excess N is subject to processes such as leaching, denitrification, volatilization, and erosion (Raun and Johnson, 1999; van Kessel and Hartley, 2000). In recent years, concerns over NO_3-N pollution into ground water from leaching and runoff have practitioners interested in improving N management strategies. Biological nitrogen fixation is an economical and sustainable alternative for supplying N to dry bean (Thilakarathna and Raizada, 2018). By reducing N input, therefore simultaneously increasing symbiotic nitrogen fixation and nitrogen use efficiency, crop input cost and the negative impacts of unused nitrogen in the environment may be reduced.

Sulfur

Sulfur (S) is required in high amounts because dry bean has a high protein content (Nascente et al., 2017). According to Sullieman et al. (2013), plants that acquire N by SNF have a greater S requirement than plants which only use soil N because S plays a significant role in N assimilation by N_2 fixing bacteria. If S deficient, grain yield potential may decrease due to reduction in plant growth and formation of branches, flowers, and pods (Fageria et al., 2011). In a growth chamber under controlled environmental conditions, Ruiz et al. (2005) determined S deficient bean plants resulted in low NO_3-N assimilation and biomass production. Furthermore, Pandurangan et al. (2015) observed S deficient bean plants reduced grain quality because storage proteins in developing seeds was altered. Due to the close linkage between S and N, failure to meet plant S demand may decrease N use efficiency and enhance the risk of N loss to the environment (Schnug and Haneklaus, 2005; Norton et al., 2013).

Plants roots almost exclusively take up sulfur as SO_4-S. The primary sources of readily available plant S are soil organic matter and atmospheric S deposition (Warncke et al., 2009). However, like N, environmental conditions can influence organic S mineralization and immobilization, the movement of S in the soil profile, and uptake of SO_4-S by plants (Havlin et al., 2013). If soil temperature, pH, and moisture are unsuitable for microbial activity, the decomposition of organic materials from plant and animal residues may be reduced and soil S levels will decrease. In addition, the S content of decomposing material may also influence the rate at which decomposition occurs. When large amounts of OM residues are added to the soil, especially for those with a large C:S ratio (e.g., straw), adequate N and S availability is required to stimulate decomposition or otherwise a temporary N or S deficiency may occur in the subsequent crop (Havlin et al., 2013). In the soil SO_4-S is transported to the roots by mass flow and diffusion but because SO_4-S in the soil solution is weakly adsorbed (Ishiguro & Makino, 2011), especially in sandy soils low in OM, it is readily subject to leaching.

Historically, S application has not been recommended for dry bean production in Michigan because most soils should supply adequate S to meet crop S needs (Warncke et al., 2009). Studies in the past with S-responsive crops grown on potentially S-deficient sites in Michigan have generally not shown a beneficial response from S fertilizer additions (Warncke et al., 2009). However, a reduction in atmospheric S deposition and S containing inputs coupled with increased sulfur removal from high yielding crops has practitioners questioning the need for S fertilizer application (McGrath and Zhao, 1995; Sawyer & Barker, 2002; Warncke et al., 2009; Culman et al., 2020). Between 1980 and 2019, the average annual atmospheric deposition of S in southern Michigan has decreased by 85% (National Atmospheric Deposition Program, 2019). Because the exploitation of S accumulated in deeper soil layers by plant roots is limited during early growth, S fertilization at early stages may provide sufficient S supply throughout a crop's growth cycle (Hitsuda et al., 2005). However, previous studies in soybean have shown that all potential S sources (i.e., OM, residual soil S, S-deposition, and fertilizer S), should be considered when determining S supply and availability (Kaiser and Kim, 2013; Norton et al., 2013; Quinn and Steinke, 2019). Although soils high in SO_4-S may indicate the likelihood of a response to S application is low, it is difficult to diagnose soil S fertility through soil analysis because there is a large variation in the S content among different soil layers, therefore, a plant analysis is the best diagnostic tool for identifying S availability (Sawyer and Barker, 2002; Hitsuda et al., 2005; Culman et al., 2020). Culman et al. (2020) suggest the application of 10-20 lb S/acre should supply adequate S for grain crops if a S deficiency is expected. In Poland, Glowacka et al. (2019) found the application of 45 lb S/acre increased grain yield by 14.5% and improved grain quality, thus concluding S fertilization should be included in the crop management practices of dry bean. In a systemic review of crop yield responses to S fertilization in Brazil, S application increased average grain yield 12% in 50% (n = 6) of dry bean studies (Pias et al., 2019). Under a sprinkler-irrigated and no-tillage system with S rates of 0, 9, 18, 36, and 54 lb S/acre, Nascente et al. (2017) observed 6 dry bean cultivars did not responded differently to S application. Moreover, other legumes such as soybean have generally produced inconsistent plant responses to supplemental S application. Bluck et al. (2015) did not observe a grain yield increase in response to S application under conditions with sufficient S tissue concentrations across 16 site-years. Quinn and Steinke (2019) did not significantly increase soybean grain yield across three site-years when potassium thiosulfate was surface banded at R1.

Sulfur fertilizers contain either SO_4-S, elemental S, or a mixture of (SO_4-S + elemental S). When applied directly before crop planting, SO_4-S fertilizer is readily available, whereas elemental sulfur must be oxidized to SO_4-S by soil microbes prior to plant uptake. Furthermore, the oxidation process to convert elemental sulfur into SO_4-S is slow and requires soil environmental conditions (i.e., temperature and moisture) are suitable for aerobic microbial activity (Havlin et al., 2013). However, unlike SO_4-S, elemental sulfur is not mobile in the soil and will not readily leach, thus it is commonly used in fall applications. Although a combination of both SO_4-S and elemental S may be useful to provide both an immediate and prolonged source of S (Norton et al. 2013), grain yield response to elemental S or granular (SO_4-S + elemental S) fertilizer application is inconsistent in past research. In a review of laboratory, greenhouse, and field studies of S fertilizer sources, Chien et al. (2016) concluded granular fertilizers containing elemental S or a combination of elemental S and ammonium sulfate provides less available S than traditional SO_4-S based fertilizer sources for field crops within the first year of S application. However, Purucker and Steinke (2020) observed the application of a granulated SO_4-S + elemental S) fertilizer increased grain S accumulation by 8% potentially due to delayed S availability from elemental S.

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CHAPTER 2

SOYBEAN SEEDING RATE AND NUTRIENT MANAGEMENT STRATEGIES IMPACT ON PLANT GROWTH AND GRAIN YIELD UNDER IRRIGATED AND NON-IRRIGATED SYSTEMS

Abstract

Greater nutrient availability may support soybean (*Glycine max* L. Merr.) yield potential through increases in total dry matter (TDM) production and nutrient uptake. However, it is uncertain if fertilizer application timing and placement strategies across seeding rates under irrigated and non-irrigated conditions can increase grain yield. Two multi-year trials were established near Lansing, MI to investigate soybean dry matter (DM) and nutrient accumulation, and partitioning, grain yield, and net economic return. Seeding rates included 148,000, 297,000, and 445,000 seeds ha^{-1}. Fertilizer strategies were no fertilizer, 168 kg MESZ ha^{-1} (12-40-0-10-1-N-P-K-S-Zn) applied five centimeters to the side and five centimeters below the seed (5x5) at planting, 150 L of liquid potash (LK) ha^{-1} (0-0-28-N-P-K) applied using a Y-drop applicator near growth stage V6, 140 L of ammonium polyphosphate (AP) ha^{-1} (10-34-0-N-P-K) applied using a Y-drop applicator near growth stage R1, and a combination of the MESZ, LK, and AP fertilizer applications (All). Early season (V4) DM and nutrient accumulation significantly increased with seeding rates ≥ 297,000 seeds ha^{-1} and MESZ in the MESZ and All fertilizer treatment. Seeding rate and fertilizer application did not interact to increase grain yield, indicating seeding rates responded similarly to fertilizer application. The 148,000 seeds ha^{-1} rate significantly decreased yield at two of four site-years while no yield differences were observed between seeding rates at the remaining two site-years. Fertilizer application significantly influenced total dry matter

accumulation in one of four site-years and nutrient accumulation across all site-years but did not impact grain yield. Lack of an interaction between seeding rate and fertilizer application coupled with unrealized yield gains from fertilizer application suggest producers should alternatively focus on other farm management practices rather than supplemental fertilizer application strategies, especially when soil nutrient concentrations are at or above critical.

Introduction

Increased climate variability combined with volatile soybean commodity prices (i.e. 50% increase from 2020 to 2021) have piqued grower interest for more intensive nutrient management strategies (USDA-NASS, 2021). Additionally, prolonged mid- to late-summer periods with insufficient soil moisture especially during pod formation and grain-fill has practitioners questioning whether supplemental irrigation may also impact fertilizer strategies between irrigated and non-irrigated environments. Seeding rate and fertilizer placement are two influential factors affecting nutrient uptake and grain yield (Purucker and Steinke, 2020). Interplant competition and subsequent total dry matter accumulation may influence nutrient uptake, thus seeding rates that maximize early season dry matter may be able to maintain soybean yield potential during increasingly unpredictable late-season temperature and precipitation fluctuations across the north-central United States (Duncan, 1986; Egli 1988b; Southworth et al., 2000). Although soil P, K, secondary, and micronutrients concentrations in combination with crop responsiveness may largely dictate whether a grain yield response occurs to fertilizer application, few data exist concerning the manipulation of seeding rate, soil moisture (i.e., irrigation), and fertilizer placement and timing on nutrient accumulation, total dry matter partitioning, and grain yield.

Earlier soybean planting dates in response to warmer spring air and soil temperatures and reduced tillage practices have prompted greater consideration for the use of starter fertilizers in soybean production systems. In Michigan, starter fertilizer may often be placed in a subsurface band 5 cm below and 5 cm to the side of the seed (5x5) as this positioning reduces the risk for salt injury and increases fertilizer efficiency by placing plant-available nutrients within reach of developing plant roots, which may often result in greater early season vegetative growth and nutrient uptake (Touchton et al., 1986; Vitosh et al., 1995; Rutan and Steinke, 2018). Osborne and Riedell (2006) found starter N increased V3-V4 soybean biomass, plant N, and grain yield in 2 of 3-site-years. Research in Ohio determined diammonium phosphate fertilizer applied in a subsurface band at planting increased V2 growth but did not impact R1 growth or grain yield (Hankinson et al., 2015). Early season soybean responses to starter fertilizer are often thought to be the result of limited early-season biological N fixation (BNF), decreased spring nutrient mineralization and availability (e.g., N and P), and reduced seedling root growth in cool, wet soils (Bergersen, 1958; Hardy et al., 1971; Ray et al., 2005; Warncke et al., 2009; Ciampitti and Salvagiotti, 2018). While N and P are typically the primary nutrients applied in a starter fertilizer, other nutrients including S and Zn have increased in usage due to reductions in atmospheric S deposition, use of high concentration fertilizers and perceived micronutrient deficiencies (McGrath and Zhao, 1995; Chien et al., 2009; Sutradhar et al., 2017). Bluck et al. (2015) found the application of S as gypsum did not influence grain yield but Kaiser and Kim (2013) reported sulfur broadcast or applied in starter increased V5 S plant concentration and uptake, R1 uppermost trifoliate S concentration, grain S concentration, and grain S removal. Sutradhar et al. (2017) found ZnO broadcasted on the soil surface before planting did not increase mean trifoliate Zn concentration or grain yield. Although soil and environmental factors will influence soybean response to starter fertilizer (e.g., soil temperature, moisture, and pH), greater early season vegetative growth and nutrient uptake from starter fertilizer application may support increased yield potential under some conditions (Sorensen and Penas, 1978; Osborne and Riedell, 2006; Purucker and Steinke, 2020).

Between 1923 and 2008, soybean grain yield from maturity groups II and III increased at a rate of 23 kg ha^{-1} $year^{-1}$ (Rincker et al., 2014). Greater grain yield during this period may partly be due to increased TDM through advancements in genetics and agronomic practices (Specht et al., 1999; De Bruin and Pederson, 2009; Rincker et al., 2014; Rowntree et al., 2014). Rowntree et al. (2014) found genetic improvement in TDM was the product of greater DM accumulation at late reproductive stages (i.e., after the onset of R4) and not vegetative growth. Suhre et al. (2014) determined seed yield was maximized at greater seeding rates for both old and new cultivars, but newer cultivars seeded at lower plant populations demonstrated greater plasticity by producing additional pods on plant branches. When avoiding stress during vegetative growth, decreased seeding rates may achieve similar crop growth rates and grain yield as greater seeding rates while simultaneously reducing seed cost and interplant competition for water and nutrients (Alessi and Power, 1982; Board, 2000). However, greater interplant competition from increased seeding rates generally results in quicker canopy closure, reduced weed emergence, increased soybean growth at early development stages, and some degree of protection against poor seedling emergence (Hamman et al., 2002; Harder et al., 2007; Chen et al., 2011).

Previous research quantified nutrient uptake, partitioning, and removal patterns in modern soybean production systems across fertility regimes within a yield range of 3000 to 6000 kg ha^{-1} (Bender et al., 2015; Gaspar et al. 2017a, 2017b, 2018). Closely resembling DM accumulation, N, P, S and Zn uptake were evenly distributed during vegetative and seed-filling growth phases, emphasizing the importance of sufficient soil nutrient concentrations to accommodate season-long nutrient accumulation (Bender et al., 2015). However, more than 70% of total K uptake has been found to occurr before late reproductive stages and unlike N and P, seed K demands rely heavily on vegetative remobilization after R5 (Bender et al., 2015; Gaspar et al., 2017a, 2017b). Although soybean nutrient requirements are generally field and year specific, higher grain yields often support a greater reliance on continuous soil-derived N, P, and S availability past R5.5 rather than vegetative remobilization (Gaspar et al. 2017a, 2017b, 2018). Greater yields have been associated with additional early season nutrient uptake, higher peak uptake rates, extended nutrient uptake duration, and greater late-season uptake quantities. (Bender et al., 2015; Gaspar et al. 2017a, 2017b, 2018). Peak uptake of N, P, and K generally ranges from R3 to R5, R2 to R4, and R1 to R3, respectively (Bender et al., 2015; Gaspar et al. 2017a, 2017b). In high yield environments (> 5000 kg ha^{-1}), identifying peak uptake periods has been suggested as to guide in-season fertilizer applications (i.e., N, P, and K) for greater synchrony between peak nutrient uptake and late season nutrient availability (Bender et al., 2015; Gaspar et al. 2017a, 2017b, 2018). However, previous research of in-season fertilizer applications was inconsistent. Salvagiotti et al. (2009) hypothesized accelerated leaf senescence due to constrained seed N demand from insufficient soil N and a late season decline in BNF would shorten the duration of crop photosynthesis, thus impacting grain yield. Freeborn et al. (2001) found R3 supplemental N fertilization in yield environments ranging from 2400 to 5300 kg ha^{-1} did not increase grain yield concluding N supplied via fixation and N mineralization was adequate in the Mid-Atlantic Coastal Plain. In Michigan, Quinn and Steinke (2019) found potassium thiosulfate R1 surface banded at above critical soil test K concentrations did not influence grain yield. Although not soil applied, Haq and Mallarino (2000) observed foliar applying various rates of a commercial 3-8-15 fertilizer tended to increase grain yield when soil or weather conditions reduced plant growth and N, P, and K availability. The objective of this study was to evaluate the effects of seeding rate and fertilizer strategy in both irrigated and non-irrigated medium-textured soils on DM production, nutrient partitioning and accumulation, grain yield, economic return, and whether the potential for greater DM production from decreased seeding rates affected the potential for nutrient accumulation.

Materials and Methods

Field trials were conducted in 2019 and 2020 at the Michigan State University South Campus Research Farm near Lansing, MI (42º42′37.0″N, 84º28′14.6″W) on an irrigated and non-irrigated Capac Loam soil (fine-loamy, mixed, active, mesic Aquic Glossudalf) and at the Michigan State University AgBioResearch Mason Research Farm near Lansing, MI (42º37′44.2″N, 84º25′56.3″W) on a non-irrigated Conover Loam soil (fine-loamy, mixed, active, mesic Aquic Hapludalfs) in 2020. All sites were previously cropped to corn (*Zea mays* L.), autumn chisel plowed (20-cm depth), and spring field cultivated (10-cm depth) prior to planting. A Micro Rain (model MR58RLBP) traveling irrigator (Micro Rain, Yukon, OK) provided 16.5 and 20 cm of supplemental water throughout the growing season at times of peak evapotranspiration and low soil moisture at the irrigated site in 2019 and 2020, respectively. Soil samples (20-cm depth) were collected prior to nutrient application, ground to pass through a 2-mm sieve, and analyzed for soil chemical properties (Table 2.01). Full season pest control followed Michigan State University best management practices. At the irrigated 2020 site, pyraclostrobin (carbamic acid, [2-[[[1-94-chlorophenyl)-*1H*-pyrazol-3-yl]methyl]phenyl]methoxy-, methyl ester) was applied at R3 to prevent foliar soybean diseases.

Environmental data were collected using the Michigan State University Enviro-weather (https://enviroweather.msu.edu, Michigan State University, East Lansing, MI). Precipitation and temperature 30-year averages were obtained from the National Oceanic and Atmosphere Administration (NOAA, 2019).

Trials were arranged in a randomized complete block split-plot design with four replications. The main plot factor was seeding rate and the subplot factor was fertilizer application. Seeding rates consisted of 148,000, 297,000, and 445,000 seeds ha^{-1}. Plants stands at the irrigated and non-irrigated site were within 10 and 33% of the targeted seeding rates in 2019 and 2020, respectively, as evidence by stand counts (Fehr and Caviness, 1977; Hicks et al., 1990). Fertilizer treatments consisted of a non-fertilized control, 168 kg MicroEssentials® SZ® (MESZ) (Mosaic CO., Plymouth, MN) ha^{-1} (12-40-0-10-1 N-P-K-S-Zn) applied 5-cm below and 5-cm to the side of the seed (5 x 5), 150 L of liquid potash (LK) ha^{-1} (0-0-28 N-P-K) applied using a Y-drop applicator near V6, 140 L of ammonium polyphosphate ha^{-1} (AP) (10-34-0 N-P-K) applied using a Y-drop applicator near R1, and a combination of the MESZ, LK, and AP fertilizer treatments referred to as the (All) treatment. Individual 6-row plots measured 12.2 m in length and 4.6 m in width. The variety ‘S170115’, and ‘S76420724’ (Stine Seed Co., Adel, IA) was planted in 76-cm rows using a Monosem planter (Monosem Inc., Kansas City, KS) in Lansing on 28 May 2019 and on 07 May 2020, respectively.

Aboveground plant biomass was sampled from five consecutive plants at V4, R2, R5, and R8 when at least 50% of the crop achieved each respective growth stage (Fehr & Caviness, 1977). Plants were partitioned into leaves, stems and petioles, flowers and pods, and grain (Bender et al., 2015). 1-cm by 1-cm netting was assembled immediately prior to the onset of leaf drop to retain senesced DM. Dry weight was determined by drying plant tissues at 66°C to 0%

moisture. Total DM accumulation was reported as the sum of all plant components. V4 and R8 aboveground plant components, and R8 grain samples were analyzed for N (AOAC, 1995a), P (AOAC, 1995b), K (AOAC, 1995b), S (AOAC, 1995b), and Zn (AOAC, 1995b). Nutrient accumulation (kg ha^{-1}) was calculated from nutrient concentration, DM accumulation, and plant density. Grain yield, moisture, and test weight were determined by harvesting the center two rows of each plot with a research plot combine (Kincaid Equipment Manufacturing, Haven, KS). Final yield was adjusted to 135 g kg^{-1} moisture. Economic return was estimated using an average local cash price of \$0.32 and \$0.51 kg^{-1} in 2019 and 2020, respectively, and input costs of \$109, \$810, \$111, and \$1,030 ha^{-1} for MESZ, LK, AP, and the All applications, respectively. Nutrient application costs of \$3.81 and \$29.65 ha^{-1} were estimated for the 5 x 5 subsurface application and Y-drop application, respectively, using Michigan State University Extension Custom Machine and Work Rate Estimates (Stein, 2019). Seed cost for 140,000 seeds ha^{-1} was estimated at \$50.00. Net economic return was calculated using a partial budget subtracting input cost from gross revenue (i.e., grain price multiplied by yield).

Statistical analyses were performed using PROC GLIMMIX in SAS 9.4 (SAS Institute, 2012) at $\alpha = 0.10$. Site-year, seeding rate, and fertilizer application were considered fixed effects and the replication as random. Normality of residuals were examined using the UNIVARIATE procedure ($P \leq .05$). Squared and absolute values of residuals were examined with Levene's Test to confirm homogeneity of variances ($P \leq .05$). Least square means were separated using the LINES option of the slice statement when ANOVA indicated a significant interaction ($P \leq .10$). Pearson product-moment correlations were derived using the REG procedure of SAS to investigate the relationship between DM accumulation with grain yield and final DM accumulation with R8 grain nutrient accumulation.

Results and Discussion

Environmental Conditions

Total growing season (May-September) precipitation was within 5% of the 30-yr average across years (Table 2.02). However, mean 2019 monthly precipitation was 29 and 108% above the 30-yr average in May and June, respectively, and 42% and 78% below the 30-yr average for July and August, respectively, creating contrasting early and late-season soil moisture conditions. Mean 2020 monthly precipitation was below the 30-yr average by 16, 42, and 16% in June, July, and August, respectively creating deficit July through August precipitation (i.e., greater than 10% below the 30-yr average) which may have limited vegetative growth, grain-fill, yield potential, and nutrient movement and uptake at the non-irrigated sites. Mean monthly air temperatures across both years were within 2.5 ˚C of the 30-yr average (Table 2.02).

Dry Matter Accumulation and Partitioning

Poor seedling emergence from soil crusting at the irrigated and non-irrigated 2020 locations reduced plant stands by up to 33% below the targeted seeding rates and possibly limited DM production in 2020 as compared to 2019. However, earlier soybean planting (i.e., 21 d earlier in 2020 than 2019) may have potentially increased 2020 vegetative and reproductive growth periods thereby also increasing DM accumulation (Hu and Wiatrak, 2012). Dry matter accumulation at V4 (kg ha^{-1}) was significantly influenced by seeding rate ($P < 0.01$) across all site-years (i.e., irrigated and non-irrigated) (Table 2.03, 2.04). As seeding rate increased from 148,000 to 445,000 seeds ha^{-1} at irrigated and non-irrigated sites, V4 dry matter (V4DM) concomitantly increased. Greater plant populations (e.g., > 125,000 plants ha^{-1}) have been shown to produce less DM $plant^{-1}$ near 30 d after emergence compared to low plant populations (e.g., ≤ 125,000 plants ha^{-1}) due to decreased plant growth rates ($g\ m^{-2}\ d^{-1}$) from greater interplant competition (Board, 2000; Purucker and Steinke, 2020). However, results from the current study suggest greater V4DM plant^{-1} (data not shown) at 148,000 seeds ha^{-1} was not sufficient to overcome reductions in DM per acre as the result of greater seeding rates (i.e., ≥ 297,000 seeds ha^{-1}). Seeding rate continued to significantly influence DM accumulation until R2 at which point accelerated post-R1 crop growth rates produced no differences in R5 dry matter (R5DM) and R8 total dry matter (R8TDM) (Table 2.03, 2.04). Total R2 dry matter (R2DM) accumulation within seeding rates accounted for 46-53% (irrigated 2019), 45-63% (non-irrigated 2019), 15-28% (irrigated 2020), and 14-23% (non-irrigated 2020) of the season-long total aboveground dry matter (data not shown). Previous research reported diminished aboveground biomass responses from greater seeding rates due to increased competition for water during dry soil conditions (Alessi and Power, 1982; Purucker and Steinke, 2020). In the current study, similar results between seeding rates at the irrigated and non-irrigated sites at R5 despite deficit precipitation (i.e., > 10% below 30-yr average) during July and August in both years suggest lack of moisture likely did not offset the vegetative responses observed at V4 and R2. Instead, greater crop growth rates due to less interplant competition from 148,000 and 297,000 seeds ha^{-1} may have reduced the DM difference between R2 and R5 (Wells, 1993; Carpenter and Board. 1997a; Egli, 1998a; Ball et al., 2000; De Bruin and Pedersen, 2008; Lee et al., 2008). Although no differences in R8TDM between seeding rates existed, a likely decrease in competition for water from irrigation increased R8TDM 2,978 and 5,081 kg ha^{-1} across seeding rates in 2019 and 2020, respectively compared to rain-fed conditions.

Relative to the treatments which did not receive fertilizer before V4 (i.e., non-fertilized, LK, and LP) the MESZ and All (which only included MESZ by V4 growth stage) treatments produced greater V4DM across site-years (Table 2.03, 2.04). The MESZ is a co-granulated fertilizer containing N, P, S, and Zn and was applied 5 cm below and 5 cm to the side of the seed at planting (i.e., starter fertilizer). Starter fertilizer for soybean may increase early-season vegetative growth due to limited BNF (biological nitrogen fixation) and N mineralization from SOM (soil organic matter) during spring soil conditions (Ray et al., 2006; Osborne and Riedell, 2006; Ciampitti and Salvagiotti, 2018). Previous research reported increased early season vegetative growth from starter N+P, N+P+S, or N+P+S+Zn fertilizers, but further analysis suggested greater early season vegetative growth was primarily due to N rather than P, S, or Zn (Kaiser and Kim, 2013; Hankinson et al., 2015; Purucker and Steinke, 2020). In the current study, cool soil temperatures at planting (13.3-18.2 ˚C) and moderate SOM concentrations (21-26 g kg^{-1}) may have placed a greater reliance on soil-derived N due to minimal BNF contributions until V2-V4 indicating the potential for N in MESZ fertilizer to increase V4DM (Taylor et al., 2005; Tamagno et al., 2018). Considering that visual P, S, and Zn deficiencies were not observed, soil test P concentrations (20-87 mg kg^{-1}) were sufficient, and few data exist or do not support early-season DM responses to S or Zn application, it is unlikely that P, S, or Zn within MESZ increased V4DM (Boem et al., 2007; Warncke et al., 2009; Kaiser and Kim, 2013; Hankinson et al., 2015). The 2019 R2DM, R5DM, and R8TDM were significantly influenced by fertilizer strategy at the irrigated site compared to R2DM and R5DM without irrigation (Table 3, 4). Non-irrigated results agree with Purucker and Steinke (2020) who found early-season DM differences from MESZ application likely diminished post-R1 due to accelerated crop growth rates which peak near R3-R4 (Bender et al., 2015; Gaspar et al., 2017a). In 2019, August precipitation was 6.4 cm below the 30-yr average, indicating that continued DM differences with irrigation may be attributed to supplemental water to help sustain biomass production during critical reproductive growth periods (i.e., pod- and seed-fill) (Andriani et al. 1991; Torrion et al., 2014; Wingeyer et al., 2014). Within fertilizer strategy, R8TDM ranged from 6507-8385 kg ha^{-1} (irrigated 2019) and 4988-6401 kg ha^{-1} (non-irrigated 2019) (Table 2.03, 2.04). The All fertilizer treatment increased irrigated R8TDM 24% compared to the non-fertilized control, but no differences occurred between the remaining fertilizer strategies and the non-fertilized control suggesting that the MESZ component within the All treatment largely caused R8TDM differences. In 2020, R2DM and R5DM were significantly influenced by fertilizer strategy at the irrigated site compared to only R2DM without irrigation (Table 2.03, 2.04). Similar to 2019, supplemental water likely influenced late-season DM differences at the irrigated site but white mold infection late into the 2020 growing season affected DM accumulation beyond R5 due to early plant senescence and death (data not shown) (Chen and Wang, 2005; Mueller et al., 2017). With supplemental water extending early-season DM differences later into the growing season, growers solely focusing on intensive management and high yield potential (i.e., irrigation, higher plant populations, and greater soil fertility) may need to consider risks for greater disease occurrence (e.g., white mold) and remember that factors such as cultivar selection, increased row width, and foliar fungicide applications may be required to mitigate disease incidence (Grau et al., 1994).

Seeding rate and fertilizer application affected V4DM partitioning (data not shown). Averaged across seeding rate and fertilizer treatments, V4DM partitioned between leaves or stems/petioles ranged from 64-77% and 23-36%, respectively for irrigated 2019 and 2020 compared to 66-72% and 28-34% for non-irrigated 2019 and 2020. Except for the non-irrigated 2020 site, low seeding rates significantly increased the proportion of V4DM partitioned to leaves and decreased the proportion of V4DM partitioned to stems/petioles compared to increased seeding rates (i.e., $\geq$ 297,000 seeds ha^{-1}). Greater early-season V4DM partitioning to leaf tissue from the 148,000 seeds ha^{-1} rate was likely due to decreased interplant competition that supported greater light interception and efficiency (i.e., photosynthetic capacity), critical to the compensatory yield ability of soybean at low plant populations (Carpenter and Board, 1997b; Ball et al., 2000; Board, 2000). In 2019, MESZ and All (which only included MESZ by V4 growth stage) applications significantly increased the proportion of V4DM partitioned to stems/petioles and decreased the proportion of V4DM partitioned to leaves compared to the non-fertilized control (data not shown). Although early-season DM accumulation is largely partitioned into leaf tissue until the initiation of reproductive growth (Gaspar et al., 2017a), results indicate greater V4DM accumulation from MESZ was the result of increased stem/petiole growth. Regardless of DM partitioning, greater early-season DM from sub-surface fertilizer application provide greater soybean nutrient accumulation.

Averaged across seeding rate and fertilizer treatments, R8TDM partitioned to leaves, stems/petioles, pods, or grain ranged from 11-17%, 29-41%, 13-18%, and 25-40%, respectively for irrigated 2019-2020 compared to 12-16%, 22-27%, 15-21%, 40-44% for non-irrigated 2019-2020 (data not shown). Environmental factors including precipitation will influence DM allocation, but the differences between irrigated and non-irrigated 2019 R8TDM partitioning were minimal despite poor pod and seed-fill conditions from below average August precipitation (i.e., 78% below the 30-yr average) (Chen and Wiatrak, 2010). However, R8TDM partitioned to grain (i.e., harvest index) appeared to be greater for non-irrigated (42-44%) than irrigated (38-40%) soybeans, suggesting irrigation produced additional biomass in excess of soybean growth and yield requirements. While the 148,000 seeds ha^{-1} rate produced more stem/petiole R8DM per plant (data not shown), greater seeding rates (i.e., $\geq$ 297,000 seeds ha^{-1}) increased the proportion of R8TDM partitioned to stems/petioles at three of four site-years. Moreover, plant height and stem diameter (data not shown) indicate additional stem/petiole DM per plant from 148,000 seeds ha^{-1} was due to a thicker rather than elongated main stem and the production of additional lateral branches. In two of three site-years, where seeding rate influenced stem/petiole partitioning, the proportion of R8TDM partitioned to grain was maximized by 148,000 seeds ha^{-1}. Individual plant data (i.e., R8TDM, R5 stem diameter, and R5 plant height) combined with R8TDM partitioning results suggest the potential for the 148,000 seeds ha^{-1} rate to remobilize a greater proportion R8TDM from the main stem and lateral branches to the grain existed, thus increasing harvest index compared to increased seeding rates (i.e., ≥ 297,000 seeds ha^{-1}). Bender et al. (2015) found approximately twice the amount of K was remobilized from stem than leaf tissue, indicating greater stem/petiole remobilization from decreased seeding rates (i.e., 148,000 seeds ha^{-1}) may serve to increase the relative proportion of grain K content to total nutrient accumulation. Differences in R8TDM partitioning due to fertilizer strategy were minimal and agree with Bender et al. (2015) and Purucker and Steinke (2020). Due to dry matter partitioning largely regulating nutrient partitioning (Marcelis, 1996; Engels et al., 2012), lack of R8TDM differences within the fertilizer treatment suggest no differences in R8 nutrient partitioning should be expected (data not shown).

Nutrient Accumulation

Nitrogen, P, K, S, and Zn uptake (kg ha^{-1}) at V4 across irrigated and non-irrigated sites were less than 10% and 19% of total N, P, K, S, and Zn uptake in 2019 and 2020, respectively, closely resembling the results from Bender et al. (2015) (Table 2.05, 2.06). The 445,000 seeds ha^{-1} rate along with MESZ and All (which only included MESZ by V4 growth stage) treatments generally increased early-season (V4) aboveground N, P, K, S and Zn accumulation (kg ha^{-1}) and the percentage of season-long N, P, K, S, and Zn accumulation at V4 across site-years (data not shown). Correlation analysis indicated a positive relationship between V4DM and N, P, K, S, and Zn accumulation (r = 0.85-0.99, P < 0.01), suggesting greater DM production from the 445,000 seeds ha^{-1} rate or the MESZ, and All (which only included MESZ by V4 growth stage) fertilizer treatments may have facilitated greater nutrient uptake (Bender et al., 2015). Gaspar et al. (2017a, 2017b, 2018) reported greater grain yields (i.e., 5500 kg ha^{-1}) and greater total nutrient uptake were associated with a shorter "lag phase" during the first 20 DAE. A greater percentage of season-long nutrient accumulation at V4 suggests that either the 445,000 seeds ha^{-1} rate or MESZ and All (which only included MESZ by V4 growth stage) treatment application likely reduced the "lag phase" of soybean nutrient accumulation thereby increasing greater early season nutrient accumulation and the potential for late-season vegetative nutrient remobilization. However, previous research indicated that most grain nutrient demand was removed from the soil during grain-fill rather than vegetative remobilization (Bender at al., 2015; Gapsar et al., 2017a, 2017b, 2018) indicating greater early-season nutrient uptake may not always translate into greater grain yield.

Total R8 aboveground nutrient accumulation (kg ha^{-1}) was significantly impacted by seeding rate under irrigation 2019 and without irrigation 2020 (Table 2.07, 2.08). Nitrogen was the only nutrient influenced by seeding rate at the irrigated 2019 site compared with N, P, K, and Zn at the non-irrigated 2020 site. Where total N, P, K, S, and Zn accumulation were significantly affected, 297,000 and 445,000 seeds ha^{-1} generally maximized N, P, K, S, and Zn accumulation. Dry weight accumulation is the foundation for soybean nutrient accumulation (Hanway and Weber, 1971a). No significant differences in R8TDM or before the remobilization of dry matter to the seed at R5 (i.e., R5DM) existed, but variations in R8TDM partitioning within seeding rate may partly be responsible for greater total nutrient accumulation from increased seeding rates (i.e., ≥ 297,000 seeds ha^{-1}).

Total aboveground nutrient accumulation (kg ha^{-1}) at R8 was significantly influenced by fertilizer application across site-years (Table 2.07, 2.08). Compared to the non-fertilized control, MESZ, AP, and All fertilizer treatments increased total P accumulation and MESZ and All increased total S accumulation at the irrigated 2019 site while LK increased total N, P, S, and Zn accumulation at the irrigated 2020 site and MESZ increased total S accumulation at the non-irrigated 2020 site. Results suggest fertilizer applications containing P (i.e., MESZ, AP, and All) or S (i.e., MESZ and All) increased P and S uptake by promoting greater soil nutrient availability throughout the soybean growing season (i.e., MESZ and All) or just prior to peak P uptake (i.e., AP). However, lack of grain yield or quality improvements from MESZ, AP, and All fertilizer applications indicate luxury P and S consumption. The S component within MESZ contains one-half elemental S and one-half SO_4-S. Chien et al. (2016) reported granular fertilizers containing a combination of elemental S and SO_4-S provide less available S after one growing season compared to SO_4-S fertilizer sources. However, Degryse et al. (2021) found the total recovery of elemental S over five years will reach or surpass SO_4-S under leaching conditions. Although it is unclear whether the elemental S component within MESZ contributed to greater total S accumulation from the MESZ and All applications, slow oxidation of elemental S may reduce the risk for future S deficiencies or the uncertainties associated with soil S availability (Goyal et al., 2021). While LK did increase total N, P, S, and Zn accumulation under irrigation in 2020, LK does not contain N, P, S, or Zn. In 2020, R8TDM was not significantly influenced at the irrigated site but a positive correlation existed between R8TDM and total nutrient accumulation (r = 0.27-0.62, $P < 0.05$) across site-years, except for total P at the non-irrigated 2019 site.

Therefore, greater N, P, S, and Zn accumulation from LK may be the result of non-significant gains in TDM production. However, soil test K concentration in 2020 at the irrigated site (i.e., 128 mg kg) was above the critical level indicating a plant response to K application was unlikely (Cullman et al., 2020). Gaspar et al. (2017b) suggested knowledge of peak uptake rates could direct in-season fertilizer applications to match peak soybean N, P, and K uptake which occur near R4, R3, and R2 respectively. In the current study, the in-season application of AP (20 kg N ha^{-1} + 66 kg P ha^{-1}) and LK (55 kg K ha^{-1}) only increased total P and K accumulation in one of four site-years, respectively, despite below adequate soil test K concentrations (i.e., < 120 mg kg) in three of four site-years (Culman et al., 2020). In the individual site-years where the in-season application of AP and LK increased total P and K accumulation, MESZ (67 kg P ha^{-1}) also increased total P and K accumulation with no significant differences between MESZ and AP or MESZ and LK. In this specific instance for P, results suggest the application of P before peak P uptake was just as effective at increasing total P accumulation as the sub-surface application of P at planting. However, MESZ does not contain K thus it is likely greater aboveground biomass production from the sub-surface application of N, P, S, and Zn (i.e., MESZ) facilitated increased total K uptake.

Nitrogen, P, K, S, and Zn harvest index reported as the percentage of nutrient accumulation partitioned to the grain were significantly impacted by seeding rate and fertilizer treatments across site-years and ranged from 78-86% N, 71-87% P, 49-66% K, 60-76% S, and 65-78% Zn for irrigated 2019-2020 compared to 78-87% N, 79-88% P, 64-88 K, 72-85% S, and 61-80% Zn for non-irrigated 2019-2020 (data not shown). However, differences between seeding rates or fertilizer strategies were minimal and may not be considered biologically significant. The K and S harvest indices were generally greater at the non-irrigated site compared to the irrigated site with a greater percentage of total K and S partitioned to leaves, stems/petioles, and pods (data not shown) rather than to the grain, indicating the potential for luxury consumption. Grain nutrient concentrations across seeding rate and fertilizer treatments ranged from 56-67 g N kg^{-1}, 5.6-6.1 g P kg^{-1}, 19-21 g K kg^{-1}, 3.1-3.4 g S kg^{-1}, and 34-40 mg Zn kg^{-1} for irrigated 2019-2020 compared to 56-65 g N kg^{-1}, 5.2-5.7 g P kg^{-1}, 18-20 g K kg^{-1}, 2.6-3.1 g S kg^{-1}, and 39-44 mg Zn kg^{-1} to non-irrigated 2019-2020 (data not shown). Differences between irrigated and non-irrigated grain nutrient concentrations were minimal except for Zn, where Zn concentration across seeding rate and fertilizer treatments ranged from 34-35 mg Zn kg^{-1} (irrigated 2019), 38-39 mg Zn kg^{-1} (non-irrigated 2019), 37-40 mg Zn kg^{-1} (irrigated 2020), and 39-44 mg kg^{-1} (non-irrigated 2020). Zinc concentration is a primary factor to help prevent disease (i.e., diarrhea, pneumonia, and malaria) in developing countries worldwide (WHO, 2002; Shrimpton et al., 2005) signifying greater soybean Zn concentrations may offer potential health benefits for food grade soybeans produced under irrigation compared to food grade soybeans produced under non-irrigated conditions.

Grain yield

No interactions occurred between seeding rate and fertilizer treatment across site-years, indicating fertilizer applications may not require adjustments solely based on early to mid-season changes in DM accumulation due to seeding rate. Grain yields ranged from 4000-5300 kg ha^{-1} (irrigated 2019-2020) and 2200-3500 kg ha^{-1} (non-irrigated 2019-2020) (Table 2.09). Increasing seeding rate from 148,000 to 445,000 seeds ha^{-1} (i.e., 200% increase) under irrigated 2019 and 148,000 to 297,000 seeds ha^{-1} (i.e., 100% increase) without irrigation 2020 increased grain yield 10 and 20%, respectively. However, grain yield at the non-irrigated 2019 and irrigated 2020 sites was not influenced by seeding rate. Although supplemental water at the irrigated 2019 site may have reduced or eliminated interplant competition for water (Alessi and Power, 1982), incremental increases in seeding rate were not proportional to increases in grain yield possibly indicating other resources (e.g., sunlight) may have limited yield potential at the greater population densities (i.e., 297,000 seeds ha^{-1}) (Duncan, 1986; Elgi, 1988b; Walker et al., 2010). Previous research found lower than recommended seeding rates (i.e., 321,200 seeds ha^{-1}) compensate for reduced plant stands by producing additional pods on plant branches (Cox et al., 2010; Suhre et al., 2014). Lack of grain yield differences and similar pods ha^{-1} (data not shown) at the non-irrigated 2019 and irrigated 2020 site suggest 148,000 seeds ha^{-1} compensated for low plant stands by producing additional pods and grain per plant. Due to soil crusting soon after planting, the 148,000 seeds ha^{-1} rate resulted in a V2 plant stand of 102,000 seeds ha^{-1} (i.e., 31% decrease) at the non-irrigated 2020 site. In comparison, V2 plant stands at the non-irrigated 2019 site were within 1% of the desired seeding rate (148,000 seeds ha^{-1}). Despite greater August and September precipitation during pod and seed-fill in 2020 than 2019 (Table 2.02), grain yield differences at the non-irrigated site in 2020 between seeding rates were likely due to a considerably low plant stand beyond what compensatory yield on plant branches could overcome.

Grain yield was not affected by fertilizer strategy regardless of irrigation in either year. Salvagiotti et al. (2008, 2009) found soybean grain yield was more likely to respond to N applications under a high grain yield environment (> 4500 kg ha^{-1}) due to the late-season decline in soil BNF which when combined with low soil N may be insufficient to satisfy seed N demand. In the current study, average grain yield < 4500 kg ha^{-1} in three of four site-years suggests BNF and N mineralization had the potential to meet seed N requirements, reducing the likelihood of a grain yield response to N application in MESZ, AP, and All applications (Freeborn et al., 2001).

At the irrigated 2020 site, however, average grain yield exceeded 4500 kg ha^{-1}, but N application from MESZ (20 kg N ha^{-1}), AP (20 kg N ha^{-1}), and All (20 kg N ha^{-1}) did not affect grain yield indicating plants were not N deficient. Soil P concentrations across site-years were above critical (i.e., 95 to 97% of maximum yield), indicating grain yield responses to P application were not probable (Warncke et al., 2009). Although deficient soil K concentrations (i.e., < 120 mg K kg^{-1}) (Culman et al., 2020) indicated the potential for a positive grain yield response (other than irrigated 2020) to K application (i.e., LK and All), previous research reported inconsistent yield responses even when STK (soil test potassium) concentrations were considered less than optimum (Clover and Mallarino, 2013). Due to difficulties predicting soil S availability (Goyal et al., 2021), Hitsuda et al. (2004) identified seed concentrations ≤ 2.3 g S kg^{-1} as deficient. Grain S concentration in the non-fertilized control across site-years (≥ 2.6 g S kg^{-1}) implied S supply was adequate for soybean growth. However, pre-plant soil nutrient analysis indicated soil Zn concentrations were low in three site-years (1.9-3.8 mg Zn kg^{-1}) and recommended the application of 0.8-4.5 kg ha^{-1} (Zn recommendation (Warncke et al., 2009). Bender et al. (2015) observed increased nutrient uptake, total biomass production, and grain yield when using supplemental fertilization to maintain greater nutrient availability. Although fertilizer application only increased R8TDM at the irrigated 2019 site, correlation analysis indicated a positive relationship between total N, P, K, S, and Zn accumulation and R8TDM (r = 0.27-0.85, P < 0.01-0.03) across site-years with the exception for total P accumulation (r = 0.07, P = 0.60) at the non-irrigated 2019 site. Findings suggest fertilizer application increased biomass production and concomitantly nutrient uptake, thus agreeing with previous literature (Bender et al., 2015). However, grain yield did not increase despite greater R8TDM and nutrient accumulation at respective site-years. Under the current environments tested, supplemental fertilization was utilized as a tool to promote nutrient availability and increase biomass production and nutrient uptake beyond requirements for optimal grain yield (i.e., luxury consumption) regardless of seeding rate.

Economic analysis

Despite some grain yield differences (e.g., irrigated 2019 and non-irrigated 2020) net economic return was not influenced by seeding rate across site-years, indicating greater grain yield from increased seeding rates (i.e., ≥ 297,000 seeds ha^{-1}) was offset by higher seed cost (Table 2.10). Findings suggest increasing or decreasing seeding rate from 321,200 seeds ha^{-1} may be practical under the conditions tested (i.e., seed cost and grain price), but growers should consider other risks (i.e., disease, lodging, climate variability, emergence, and harvestability) associated with lower populations prior to altering seeding rate.

Net economic return was significantly influenced by fertilizer treatment across site-years. Compared to the non-fertilized control, MESZ, LK, AP, and All applications reduced 2019 net economic return regardless of irrigation. Although no grain yield differences were detected, LK and All decreased net economic return compared to the non-fertilized control at the irrigated and non-irrigated 2020 site. Lack of significant net economic return differences between MESZ, AP, and the non-fertilized control were likely the result of an increase in grain price ($0.19 kg^{-1}) from 2019 to 2020 but constant fertilizer and application costs. An upward shift in grain prices reduces the break-even soybean yield required to cover both fertilizer and application costs (Table 2.11). This decrease in break-even yield illustrates the potential for growers to capitalize on market volatility utilizing fertilizer strategies.

Conclusions

Seeding rates ≥ 297,000 seeds ha^{-1} and the sub-surface (5x5) application of MESZ both increased early-season DM and nutrient accumulation thereby providing the potential to improve grain yield. When compared to rain-fed conditions, irrigation sustained early-season DM differences later into the growing season and increased total DM production, nutrient accumulation, and grain yield. Thus supplemental water during mid- to late-summer periods without rainfall may increase the potential for a soybean response to seeding rate and fertilizer application by maintaining accelerated crop growth rates and potentially improving nutrient transport within the soil profile. Although there were no significant differences in R8TDM between 148,000, 297,000, and 445,000 seeds ha^{-1}, the 148,000 seeds ha^{-1} rate significantly reduced grain yield and total N, P, K, S, or Zn accumulation in two of four site-years compared to seeding rates ≥ 297,000 seeds ha^{-1} indicating the potential for greater DM production from low plant populations does not always affect the potential for nutrient accumulation. However, a positive correlation between total N, P, K, S, and Zn accumulation and R8TDM (r = 0.27-0.85, P < 0.01-0.03) across respective site-years supports the potential for greater DM production facilitating greater nutrient uptake. Despite plant responses from the strategic placement and timing of fertilizer in addition to seeding rate under irrigated and rain-fed conditions, grain yield was not influenced by fertilizer strategy nor was there an interaction between seeding rate and fertilizer strategy likely due to adequate soil nutrient concentrations except for deficient soil K concentrations in three of four site-years. Results suggest growers should continue focusing on soil resiliency through building or maintaining soil nutrient concentrations over time but may also consider other yield-limiting factors including variety selection, row spacing, planting date, pest and disease control, and soil moisture availability when soil nutrient concentrations are at or above critical. Under high yield environments where seed nutrient demand appears to rely more heavily on nutrient uptake from the soil rather than vegetative remobilization, more research is needed to support the effectiveness of supplemental nutrient applications including rate and timings on soybean yield.

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APPENDICES

APPENDIX A:

CHAPTER 2 TABLES

Table 2.01. Soil chemical properties and mean nutrient concentrations (0 to 20-cm depth) for irrigated and non-irrigated sites, Lansing, MI, 2019-2020.

		Soil test values[a]						
Site	**Year**	**pH**	**CEC**	**SOM**	**P**	**K**	**S**	**Zn**
			$cmol_c\ kg^{-1}$	$g\ kg^{-1}$	————	$mg\ kg^{-1}$	————	
Lansing, irrigated	2019	6.9	7.5	21	38	80	6	2.1
	2020	6.5	9.5	26	87	128	9	4.4
Lansing, non-irrigated	2019	7.5	7.5	27	86	94	7	3.8
	2020	6.7	8.8	20	20	87	7	1.9

[a]pH (1:1, soil/water) (Peters et al., 2015); CEC, cation exchange capacity (Warncke et al., 1980); SOM soil organic matter (loss-on-ignition) (Combs and Nathan, 2015); P Phosphorus (Bray-P1) (Frank et al., 2015), K potassium (ammonium acetate method) (Warncke and Brown, 2015), S sulfur (monocalcium phosphate extraction) (Combs et al., 2015), Zn Zinc (0.1 M HCl extraction) (Whitney, 2015).

Table 2.02. Monthly[a], 30-yr average[b] cumulative precipitation and air temperature, and supplemental irrigation[c] for the soybean-growing season (May-September), Lansing, MI, 2019-2020.

	Year	May	June	July	August	September	Total
Precipitation				cm			
	2019	8.5	18.3	5.8	1.8	9.3	43.7
	2020	11.0	7.4	4.2	6.9	10.9	40.4
Air Temperature				˚C			
	30-yr avg	8.5	8.8	7.2	8.2	8.9	41.6
	2019	13.4	18.3	23.2	20.3	18.5	93.7
	2020	13.8	20.2	23.5	21.3	15.8	94.6
Irrigation				cm			
	30-yr avg	14.3	19.8	21.9	21.0	16.6	93.6
	2019	0	0	5.5	10.0	1.0	16.5
	2020	0	2.8	9.9	7.6	0	20.3

[a]Monthly precipitation and air temperatures collected from MSU Enviro-weather (https://enviroweather.msu.edu).
[b]30-year averages collected from the National Oceanic and Atmosphere Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals).
[c]Supplemental irrigation was applied during times of peak evapotranspiration and low soil moisture at the irrigated site in 2019-2020.

Table 2.03. Impact of soybean seeding rate and fertilizer application on irrigated and non-irrigated V4, R2, R5, and R8 aboveground dry matter accumulation, Lansing, MI, 2019.

Site	Treatment	V4	R2	R5	R8
		kg ha^{-1}			
Irrigated	Seeding rate, seeds ha^{-1}				
	148,000	159 c[a]	3167 b	4465	7154
	297,000	230 b	3453 b	4885	6834
	445,000	310 a	4118 a	5279	7887
	P > F	<0.01	<0.01	0.22	0.26
	Fertilizer				
	Non-fertilized	175 c	3100 c	4461 b	6735 bc
	MESZ[b]	295 b	4034 b	4873 b	7916 ab
	LK[c]	179 c	2828 c	4241 b	6507 c
	AP[d]	148 d	2960 c	4560 b	6914 bc
	All[e]	368 a	4973 a	6246 a	8385 a
	P > F	<0.01	<0.01	0.04	0.07
Non-irrigated	Seeding rate, seeds ha^{-1}				
	148,000	148 c	2393 b	3488	5399
	297,000	260 b	3038 a	4016	5848
	445,000	317 a	3531 a	4055	5547
	P > F	<0.01	0.03	0.23	0.73
	Fertilizer				
	Non-fertilized	192 b	2643 b	3351 c	4988
	MESZ	312 a	3328 a	4576 a	6401
	LK	210 b	3092 ab	3826 bc	5718
	AP	201 b	2553 b	3587 bc	5535
	All	292 a	3320 a	3924 b	5349
	P > F	<0.01	0.06	<0.01	0.12

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.04. Impact of soybean seeding rate and fertilizer application on irrigated and non-irrigated V4, R2, R5, and R8 aboveground dry matter accumulation, Lansing, MI, 2020.

Site	**Treatment**	**V4**	**R2**	**R5**	**R8**
		——————————kg ha^{-1}——————————			
Irrigated	Seeding rate, seeds ha^{-1}				
	148,000	498 c[a]	1165 b	8982	8555
	297,000	805 b	1784 a	10621	10071
	445,000	937 a	1960 a	10296	8023
	P > *F*	<0.01	<0.01	0.19	0.20
	Fertilizer				
	Non-fertilized	674 b	1657 ab	9913 ab	9908
	MESZ[b]	922 a	1907 a	11542 a	8115
	LK[c]	645 b	1363 c	8843 b	8645
	AP[d]	557 b	1459 bc	8919 b	8604
	All[e]	936 a	1795 a	10614 ab	9144
	P > *F*	<0.01	<0.01	0.07	0.65
Non-irrigated	Seeding rate, seeds ha^{-1}				
	148,000	245 c	972 c	7190	7225
	297,000	446 b	1454 b	7737	8857
	445,000	613 a	1640 a	7143	7589
	P > *F*	<0.01	<0.01	0.67	0.13
	Fertilizer				
	Non-fertilized	425 b	1297 b	6953	7144
	MESZ	528 a	1536 a	7068	7939
	LK	419 b	1282 b	8370	8079
	AP	371 b	1187 b	6834	8374
	All	437 b	1475 ab	7557	7915
	P > *F*	0.07	0.05	0.45	0.76

[a]Least square means within each column followed by a common letter are not significantly different at α = 0.10.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.05. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated V4 aboveground nutrient accumulation[a], Lansing, MI, 2019.

Site	Treatment	N	P	K	S	Zn
		kg ha^{-1}				g ha^{-1}
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	5.5 c[b]	0.6 c	3.7 c	0.4 c	5.4 c
	297,000	7.0 b	0.8 b	4.8 b	0.5 b	7.7 b
	445,000	9.2 a	1.1 a	6.5 a	0.7 a	11.6 a
	P > F	<0.01	<0.01	<0.01	<0.01	<0.01
	Fertilizer					
	Non-fertilized	5.5 c	0.6 c	4.1 c	0.4 c	5.8 c
	MESZ[c]	9.3 b	1.2 b	5.5 b	0.7 b	11.1 b
	LK[d]	5.2 c	0.6 c	3.9 c	0.4 c	5.8 c
	AP[e]	4.4 d	0.5 c	3.6 c	0.3 d	4.9 d
	All[f]	11.5 a	1.5 a	7.9 a	0.8 a	13.7 a
	P > F	<0.01	<0.01	<0.01	<0.01	<0.01
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	5.2 c	0.6 c	3.4 b	0.3 c	5.0 c
	297,000	8.9 b	1.0 b	5.9 a	0.6 b	8.5 b
	445,000	10.7 a	1.3 a	6.7 a	0.8 a	10.4 a
	P > F	<0.01	<0.01	<0.01	<0.01	<0.01
	Fertilizer					
	Non-fertilized	6.7 b	0.7 b	3.9 c	0.4 b	6.0 c
	MESZ	10.6 a	1.3 a	6.4 a	0.7 a	10.0 a
	LK	7.3 b	0.8 b	5.3 ab	0.5 b	7.6 bc
	AP	6.8 b	0.8 b	4.7 bc	0.5 b	7.3 bc
	All	9.9 a	1.1 a	6.2 a	0.7 a	8.9 ab
	P > F	<0.01	<0.01	0.04	<0.01	0.02

[a]Total nutrient accumulation calculated as the sum of leaf and stem/petiole (nutrient concentration x dry matter accumulation).

[b]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

[c]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

[d]LK: liquid potassium (0-0-28 N-P-K).

[e]AP: ammonium polyphosphate (10-34-0 N-P-K).

[f]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.06. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated V4 aboveground nutrient accumulation[a], Lansing, MI, 2020.

Site	Treatment	N	P	K	S	Zn
		kg ha^{-1}				g ha^{-1}
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	19 b[b]	1.9 b	12 b	1.2 c	25 b
	297,000	31 a	3.1 a	21 a	1.9 b	41 a
	445,000	35 a	3.6 a	22 a	2.2 a	43 a
	P > F	<0.01	<0.01	<0.01	<0.01	0.01
	Fertilizer					
	Non-fertilized	26 b	2.7 b	17 ab	1.6 b	29 b
	MESZ[c]	34 a	3.3 a	20 a	2.2 a	43 a
	LK[d]	25 bc	2.6 bc	18 ab	1.5 bc	30 b
	AP[e]	22 c	2.3 c	15 b	1.4 c	27 b
	All[f]	34 a	3.5 a	21 a	2.3 a	53 a
	P > F	<0.01	<0.01	0.06	<0.01	<0.01
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	9 c	1.0 c	4.2 c	0.5 c	12 c
	297,000	16 b	1.5 b	7.4 b	1.0 b	21 b
	445,000	22 a	2.1 a	9.4 a	1.3 a	29 a
	P > F	<0.01	<0.01	<0.01	<0.01	<0.01
	Fertilizer					
	Non-fertilized	15 b	1.6	7.3	0.9 bc	20 b
	MESZ	20 a	1.8	8.3	1.2 a	27 a
	LK	15 b	1.5	6.9	0.9 bc	17 b
	AP	13 b	1.3	5.9	0.7 c	16 b
	All	16 b	1.4	6.5	1.0 b	25 a
	P > F	0.03	0.27	0.21	<0.01	<0.01

[a]Total nutrient accumulation calculated as the sum of leaf and stem/petiole (nutrient concentration x dry matter accumulation).
[b]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[c]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[d]LK: liquid potassium (0-0-28 N-P-K).
[e]AP: ammonium polyphosphate (10-34-0 N-P-K).
[f]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.07. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated R8 aboveground nutrient accumulation[a], Lansing, MI, 2019.

Site	Treatment	N	P	K	S	Zn
		kg ha^{-1}				g ha^{-1}
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	277 b[b]	25.0	113	18.5	169
	297,000	293 a	26.1	109	19.0	167
	445,000	306 a	27.0	115	19.7	177
	P > F	0.02	0.25	0.55	0.22	0.27
	Fertilizer					
	Non-fertilized	287 ab	24.2 d	107 b	18.6 ab	169
	MESZ[c]	301 a	26.1 bc	108 b	19.8 a	176
	LK[d]	277 b	24.4 cd	108 b	17.7 b	164
	AP[e]	292 ab	27.2 ab	111 b	19.1 a	167
	All[f]	303 a	28.3 a	127 a	19.8 a	179
	P > F	0.06	<0.01	0.01	0.05	0.21
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	231	21.0	73	12.7	162
	297,000	233	20.0	73	12.6	160
	445,000	236	20.2	69	12.2	151
	P > F	0.52	0.26	0.43	0.50	0.16
	Fertilizer					
	Non-fertilized	233	20.2	66 b	12.1 c	154
	MESZ	234	20.6	76 a	13.1 a	159
	LK	227	20.5	75 a	11.9 c	155
	AP	237	20.9	69 b	12.4 bc	159
	All	236	20.0	71 ab	13.0 a	162
	P > F	0.40	0.77	0.04	0.03	0.79

[a]Total nutrient accumulation calculated as the sum of leaf, stem/petiole, pod, and grain (nutrient concentration x dry matter accumulation).

[b]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

[c]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

[d]LK: liquid potassium (0-0-28 N-P-K).

[e]AP: ammonium polyphosphate (10-34-0 N-P-K).

[f]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.08. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated R8 aboveground nutrient accumulation[a], Lansing, MI, 2020.

Site	Treatment	N	P	K	S	Zn
		kg ha^{-1}				g ha^{-1}
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	360	37	195	26	271
	297,000	358	37	210	27	299
	445,000	390	41	197	29	307
	P > F	0.13	0.15	0.50	0.19	0.39
	Fertilizer					
	Non-fertilized	360 bc[a]	37 b	204	27 bc	260 c
	MESZ[c]	341 c	36 b	181	25 c	269 bc
	LK[d]	406 a	42 a	220	29 a	325 a
	AP[e]	358 bc	37 b	194	27 bc	292 abc
	All[f]	380 ab	40 ab	205	28 ab	316 ab
	P > F	<0.01	0.10	0.19	0.02	0.10
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	199 b	19 b	82 b	11	182 b
	297,000	246 a	23 a	105 a	12	225 a
	445,000	234 a	21 a	90 ab	11	209 ab
	P > F	0.02	0.03	0.07	0.12	0.06
	Fertilizer					
	Non-fertilized	223	21	85	11 b	196
	MESZ	251	22	92	13 a	223
	LK	225	20	102	11 b	197
	AP	224	21	96	11 b	207
	All	209	19	87	12 ab	204
	P > F	0.20	0.35	0.15	0.05	0.35

[a]Total nutrient accumulation calculated as the sum of leaf, stem/petiole, pod, and grain (nutrient concentration x dry matter accumulation).
[b]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[c]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[d]LK: liquid potassium (0-0-28 N-P-K).
[e]AP: ammonium polyphosphate (10-34-0 N-P-K).
[f]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.09. Soybean grain yield[a] as affected by seeding rate and fertilizer application for irrigated and non-irrigated sites, Lansing, MI, 2019-2020.

	2019		2020	
Treatment	**Irrigated**	**Non-irrigated**	**Irrigated**	**Non-irrigated**
	kg ha^{-1}			
Seeding rate, seeds ha^{-1}				
148,000	4096 b[b]	2238	4824	2849 b
297,000	4312 ab	2487	4926	3429 a
445,000	4504 a	2288	5102	3347 a
P > F	0.03	0.34	0.66	0.06
Fertilizer				
Non-fertilized	4306	2400	4768	3209
MESZ[c]	4272	2395	4933	3540
LK[d]	4170	2540	5257	3219
AP[e]	4291	2190	4787	3112
All[f]	4480	2162	5010	2961
P > F	0.32	0.36	0.48	0.31

[a]Grain yield adjusted to 135 g kg^{-1} moisture.

[b]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

[c]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

[d]LK: liquid potassium (0-0-28 N-P-K).

[e]AP: ammonium polyphosphate (10-34-0 N-P-K).

[f]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.10. Soybean seeding rate and fertilizer application effects on economic return[a] for irrigated and non-irrigated sites, Lansing, MI, 2019-2020.

	2019		2020	
Treatment	**Irrigated**	**Non-irrigated**	**Irrigated**	**Non-irrigated**
	US$ ha^{-1}		US$ ha^{-1}	
Seeding rate, seeds ha^{-1}				
148,000	1260	664	2087	963
297,000	1277	692	2090	1207
445,000	1286	575	1986	1112
P > *F*	0.77	0.15	0.31	0.15
Fertilizer				
Non-fertilized	1275 a[b]	664 a	2329 a	1533 ab
MESZ[c]	1151 b	549 b	2300 a	1589 a
LK[d]	392 c	-131 c	1738 b	698 c
AP[e]	1130 b	455 b	2197 a	1343 b
All[f]	233 d	-511 d	1354 c	308 d
P > *F*	<0.01	<0.01	<0.01	<0.01

[a]Economic return calculated as ((soybean grain price x grain yield) – partial budget costs)).
[b]Least square means within each column followed by a common letter are not significantly different at α = 0.10.
[c]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[d]LK: liquid potassium (0-0-28 N-P-K).
[e]AP: ammonium polyphosphate (10-34-0 N-P-K).
[f]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.11. Break even soybean yield[a] required to cover the partial budget costs as influenced by fertilizer application, Lansing, MI, 2019-2020.

Fertilizer	**2019**	**2020**
	$kg\ ha^{-1}$	
Non-fertilized	0	0
MESZ[b]	354	222
LK[c]	2625	1647
AP[d]	440	276
All[e]	3431	2153

[a]Break even soybean yield calculated as partial budget costs ÷ soybean grain price from 2019 (\$0.32 $kg\ ha^{-1}$) and 2020 (\$0.51 kg^{-1})

[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

[c]LK: liquid potassium (0-0-28 N-P-K).

[d]AP: ammonium polyphosphate (10-34-0 N-P-K).

[e]All: combination of MESZ, LK, and AP fertilizer applications.

APPENDIX B:

CHAPTER 2 DATA COLLECTED BUT NOT INCLUDED IN PUBLICATION

Table 2.12. Influence of soybean seeding rate and fertilizer application on irrigated and non-irrigated V4, R2, R5, and >R5-R8 percent of total aboveground dry matter accumulation, Lansing, MI, 2019.

Site	**Treatment**	**V4**	**R2**	**R5**	**>R5-R8**
		Percent (%) of total aboveground dry matter			
Irrigated	Seeding rate, seeds ha^{-1}				
	148,000	2.5 b[a]	46	66	34
	297,000	3.4 a	53	74	26
	445,000	3.9 a	53	69	31
	P > *F*	0.03	0.39	0.56	0.56
	Fertilizer				
	Non-fertilized	2.9 b	50 b	69	31
	MESZ[b]	4.0 a	54 ab	64	36
	LK[c]	2.8 b	46 b	68	32
	AP[d]	2.3 b	46 b	72	28
	All[e]	4.5 a	61 a	77	23
	P > *F*	<0.01	0.04	0.70	0.70
Non-irrigated	Seeding rate, seeds ha^{-1}				
	148,000	2.8 c	45 b	72	34
	297,000	4.5 b	54 ab	72	28
	445,000	5.5 a	63 a	72	28
	P > *F*	<0.01	0.04	0.50	0.50
	Fertilizer				
	Non-fertilized	4.0 b	55	71	29
	MESZ	4.5 ab	53	71	29
	LK	3.7 b	56	70	30
	AP	3.7 b	47	67	33
	All	5.2 a	59	70	30
	P > *F*	0.01	0.48	0.99	0.99

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.13. Influence of soybean seeding rate and fertilizer application on irrigated and non-irrigated V4, R2, R5, and >R5-R8 percent of total aboveground dry matter accumulation, Lansing, MI, 2020.

Site	**Treatment**	**V4**	**R2**	**R5**	**>R5-R8**
		Percent (%) of total aboveground dry matter			
Irrigated	Seeding rate, seeds ha^{-1}				
	148,000	6.7 b[a]	15 b	112	-12
	297,000	8.5 b	19 b	111	-11
	445,000	13.2 a	28 a	148	-48
	P > *F*	0.06	0.03	0.21	0.21
	Fertilizer				
	Non-fertilized	8.0 c	18	114	-14
	MESZ[b]	12.1 a	25	154	-54
	LK[c]	8.5 bc	17	108	-8
	AP[d]	7.8 c	20	113	-13
	All[e]	10.8 ab	22	132	-32
	P > *F*	0.02	0.28	0.28	0.28
Non-irrigated	Seeding rate, seeds ha^{-1}				
	148,000	3.4 c	14 c	100	0
	297,000	5.4 b	18 b	91	9
	445,000	8.6 a	23 a	107	-7
	P > *F*	<0.01	<0.01	0.61	0.56
	Fertilizer				
	Non-fertilized	6.1 a	18 a	102	-2
	MESZ	6.7 a	20 a	90	10
	LK	5.7 ab	17 ab	122	-22
	AP	4.5 b	15 b	83	17
	All	5.8 ab	19 a	99	1
	P > *F*	0.08	0.08	0.26	0.24

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

[c]LK: liquid potassium (0-0-28 N-P-K).

[d]AP: ammonium polyphosphate (10-34-0 N-P-K).

[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.14. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated V4 dry matter partitioning, Lansing, MI, 2019.

Site	**Treatment**	**Leaves**	**Stems/Petioles**
		Percent (%) of aboveground dry matter	
Irrigated	Seeding rate, seeds ha^{-1}		
	148,000	77 a[a]	23 c
	297,000	73 b	27 b
	445,000	70 c	30 a
	P > F	<0.01	<0.01
	Fertilizer		
	Non-fertilized	76 a	24 d
	MESZ[b]	70 d	30 a
	LK[c]	73 bc	27 bc
	AP[d]	76 ab	24 cd
	All[e]	71 cd	29 ab
	P > F	<0.01	<0.01
Non-irrigated	Seeding rate, seeds ha^{-1}		
	148,000	71 a	29 b
	297,000	69 b	31 a
	445,000	68 b	32 a
	P > F	0.06	0.06
	Fertilizer		
	Non-fertilized	72 a	28 c
	MESZ	68 c	32 a
	LK	71 ab	29 bc
	AP	69 bc	31 ab
	All	68 c	32 a
	P > F	0.01	0.01

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

[c]LK: liquid potassium (0-0-28 N-P-K).

[d]AP: ammonium polyphosphate (10-34-0 N-P-K).

[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.15. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated V4 dry matter partitioning, Lansing, MI, 2020.

Site	Treatment	Leaves	Stems/Petioles
		Percent (%) of aboveground dry matter	
Irrigated	Seeding rate, seeds ha^{-1}		
	148,000	70 a	30 b
	297,000	66 b	34 a
	445,000	64 b	36 a
	P > *F*	0.03	0.03
	Fertilizer		
	Non-fertilized	67	33
	MESZ[b]	65	35
	LK[c]	68	32
	AP[d]	68	32
	All[e]	65	35
	P > *F*	0.13	0.13
Non-irrigated	Seeding rate, seeds ha^{-1}		
	148,000	69	31
	297,000	66	34
	445,000	67	33
	P > *F*	0.48	0.48
	Fertilizer		
	Non-fertilized	68	32
	MESZ	69	31
	LK	67	33
	AP	66	34
	All	66	34
	P > *F*	0.63	0.63

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

[c]LK: liquid potassium (0-0-28 N-P-K).

[d]AP: ammonium polyphosphate (10-34-0 N-P-K).

[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.16. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated R2 dry matter partitioning, Lansing, MI, 2019.

Site	Treatment	Leaves	Stems/Petioles	Flowers
		Percent (%) of aboveground dry matter		
Irrigated	Seeding rate, seeds ha^{-1}			
	148,000	52 a[a]	46	2.3 b
	297,000	51 ab	47	2.6 b
	445,000	50 b	46	3.8 a
	P > F	0.06	0.20	0.06
	Fertilizer			
	Non-fertilized	52 a	45 c	3.3
	MESZ[b]	49 b	48 b	3.1
	LK[c]	53 a	45 c	2.8
	AP[d]	52 a	45 c	2.8
	All[e]	48 b	49 a	2.4
	P > F	<0.01	<0.01	0.50
Non-irrigated	Seeding rate, seeds ha^{-1}			
	148,000	54 a	44 b	2.6 ab
	297,000	53 a	45 b	2.8 a
	445,000	51 b	47 a	2.2 b
	P > F	0.03	0.01	0.08
	Fertilizer			
	Non-fertilized	52 bc	44 bc	3.0
	MESZ	51 c	47 a	2.2
	LK	54 a	43 c	2.3
	AP	53 ab	44 bc	2.6
	All	52 bc	46 ab	2.5
	P > F	0.03	0.03	0.24

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.17. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated R2 dry matter partitioning, Lansing, MI, 2020.

Site	**Treatment**	**Leaves**	**Stems/Petioles**	**Flowers**
		Percent (%) of aboveground dry matter		
Irrigated	Seeding rate, seeds ha^{-1}			
	148,000	59 a[a]	39 b	1.8
	297,000	54 b	44 a	1.6
	445,000	53 b	45 a	1.7
	P > F	<0.01	<0.01	0.69
	Fertilizer			
	Non-fertilized	56 a	42 b	1.5 b
	MESZ[b]	53 b	45 a	1.8 a
	LK[c]	57 a	41 b	1.7 ab
	AP[d]	58 a	41 b	1.5 b
	All[e]	53 b	45 a	2.0 a
	P > F	<0.01	<0.01	0.02
Non-irrigated	Seeding rate, seeds ha^{-1}			
	148,000	55 a	43 c	2.2 b
	297,000	53 b	44 b	2.4 ab
	445,000	52 c	46 a	2.8 a
	P > F	<0.01	<0.01	0.07
	Fertilizer			
	Non-fertilized	54 a	43 b	2.4
	MESZ	53 b	45 a	2.5
	LK	54 a	44 b	2.5
	AP	54 a	43 b	2.5
	All	52 b	45 a	2.4
	P > F	<0.01	<0.01	0.99

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.18. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated R5 dry matter partitioning, Lansing, MI, 2019.

Site	**Treatment**	**Leaves**	**Stems/Petioles**	**Flowers/Pods**
		Percent (%) of aboveground dry matter		
Irrigated	Seeding rate, seeds ha^{-1}			
	148,000	40 a[a]	50	10
	297,000	38 b	50	14
	445,000	37 b	51	11
	P > F	<0.01	0.17	0.44
	Fertilizer			
	Non-fertilized	40 a	49 b	12
	MESZ[b]	38 b	51 a	11
	LK[c]	40 a	50 b	12
	AP[d]	40 a	50 b	11
	All[e]	37 c	51 a	13
	P > F	<0.01	<0.01	0.35
Non-irrigated	Seeding rate, seeds ha^{-1}			
	148,000	40 a	46 b	13
	297,000	39 ab	47 b	14
	445,000	38 b	48 a	14
	P > F	0.06	0.04	0.66
	Fertilizer			
	Non-fertilized	40	46	14
	MESZ	38	47	15
	LK	39	47	14
	AP	40	47	13
	All	39	47	14
	P > F	0.15	0.43	0.47

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.19. Soybean seeding rate and fertilizer application effects on irrigated and non-irrigated R5 dry matter partitioning, Lansing, MI, 2020.

Site	**Treatment**	**Leaves**	**Stems/Petioles**	**Flowers/Pods**
		Percent (%) of aboveground dry matter		
Irrigated	Seeding rate, seeds ha^{-1}			
	148,000	28 a[a]	43 b	29
	297,000	27 b	45 a	27
	445,000	26 b	46 a	27
	P > F	0.02	0.08	0.38
	Fertilizer			
	Non-fertilized	28 a	45	27
	MESZ[b]	26 c	44	29
	LK[c]	28 ab	46	27
	AP[d]	27 bc	45	28
	All[e]	26 c	45	29
	P > F	0.02	0.87	0.24
Non-irrigated	Seeding rate, seeds ha^{-1}			
	148,000	27	34	39
	297,000	27	35	38
	445,000	27	36	37
	P > F	0.59	0.52	0.21
	Fertilizer			
	Non-fertilized	27	37	36
	MESZ	26	35	38
	LK	26	35	38
	AP	27	34	38
	All	28	32	40
	P > F	0.19	0.13	0.22

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.20. Impact of soybean seeding rate and fertilizer application on irrigated and non-irrigated R8 aboveground dry matter partitioning, Lansing, MI, 2019.

Site	**Treatment**	**Leaves**	**Stems/Petioles**	**Pods**	**Grain**
		Percent (%) of aboveground dry matter			
Irrigated	Seeding rate, seeds ha^{-1}				
	148,000	13	30	18 a[a]	38
	297,000	15	29	16 b	39
	445,000	14	30	16 b	39
	P > *F*	0.19	0.71	<0.01	0.64
	Fertilizer				
	Non-fertilized	15	29	17	39
	MESZ[b]	15	31	16	38
	LK[c]	13	29	18	40
	AP[d]	16	30	17	38
	All[e]	13	31	17	39
	P > *F*	0.21	0.19	0.18	0.70
Non-irrigated	Seeding rate, seeds ha^{-1}				
	148,000	16	23 b	17	44
	297,000	15	25 a	17	43
	445,000	15	27 a	15	43
	P > *F*	0.62	0.01	0.12	0.68
	Fertilizer				
	Non-fertilized	15	25 bc	17	44
	MESZ	14	26 ab	16	44
	LK	16	24 c	17	43
	AP	16	25 bc	16	43
	All	16	27 a	15	42
	P > *F*	0.26	0.04	0.62	0.76

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.21. Impact of soybean seeding rate and fertilizer application on irrigated and non-irrigated R8 aboveground dry matter partitioning, Lansing, MI, 2020.

Site	Treatment	Leaves	Stems/Petioles	Pods	Grain
		Percent (%) of aboveground dry matter			
Irrigated	Seeding rate, seeds ha^{-1}				
	148,000	14	33 b[a]	14	39 a
	297,000	13	36 b	14	36 a
	445,000	16	46 a	13	25 b
	P > F	0.14	0.01	0.25	0.03
	Fertilizer				
	Non-fertilized	14 a	39	14	33
	MESZ[b]	13 bc	38	15	34
	LK[c]	17 a	38	13	31
	AP[d]	16 ab	41	13	32
	All[e]	11 c	37	15	35
	P > F	0.02	0.81	0.33	0.83
Non-irrigated	Seeding rate, seeds ha^{-1}				
	148,000	12 b	22 c	21 a	45 a
	297,000	14 a	25 b	20 b	41 b
	445,000	14 a	27 a	19 c	40 b
	P > F	0.03	<0.01	<0.01	<0.01
	Fertilizer				
	Non-fertilized	13	24	20	42
	MESZ	13	25	20	42
	LK	14	24	20	42
	AP	13	24	20	42
	All	13	24	20	42
	P > F	0.82	0.49	0.91	0.97

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.22. Percentage of irrigated and non-irrigated season-long soybean nutrient accumulation at V4 as affected by seeding rate and fertilizer, Lansing, MI, 2019.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	2.0 c[a]	2.5 c	3.2 c	2.0 c	2.0 c
	297,000	2.4 b	3.3 b	4.5 b	2.7 b	2.4 b
	445,000	3.0 a	4.2 a	5.6 a	3.4 a	3.0 a
	P > F	<0.01	<0.01	<0.01	<0.01	<0.01
	Fertilizer					
	Non-fertilized	1.9 c	2.5 b	3.9 c	2.1 c	1.9 c
	MESZ[b]	3.1 b	4.6 a	5.1 b	3.4 b	3.1 b
	LK[c]	1.9 c	2.4 b	3.7 c	2.1 c	1.9 c
	AP[d]	1.5 d	1.9 c	3.3 c	1.6 d	1.5 d
	All[e]	3.8 a	5.2 a	6.3 a	4.3 a	3.8 a
	P > F	<0.01	<0.01	<0.01	<0.01	<0.01
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	2.4 c	2.8 c	4.7 c	2.8 c	3.1 c
	297,000	3.7 b	4.7 b	8.0 b	4.8 b	5.4 b
	445,000	4.5 a	6.2 a	9.6 a	6.1 a	6.8 a
	P > F	<0.01	<0.01	<0.01	<0.01	<0.01
	Fertilizer					
	Non-fertilized	2.9 b	3.6 b	6.1 b	3.8 b	4.0 c
	MESZ	4.5 a	6.1 a	8.7 a	5.5 a	6.5 a
	LK	3.2 b	3.9 b	6.9 b	4.2 b	4.9 c
	AP	2.9 b	3.6 b	6.8 b	3.9 b	4.6 c
	All	4.2 a	5.6 a	8.6 a	5.3 a	5.5 ab
	P > F	<0.01	<0.01	0.04	<0.01	<0.01

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.23. Percentage of irrigated and non-irrigated season-long soybean nutrient accumulation at V4 as affected by seeding rate and fertilizer, Lansing, MI, 2020.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	5.7 b[a]	5.5 b	6.5 b	5.1 b	9.3
	297,000	8.5 a	8.4 a	9.7 a	7.0 a	13.7
	445,000	9.3 a	9.2 a	11.3 a	8.0 a	14.7
	P > F	0.03	0.01	0.04	0.04	0.12
	Fertilizer					
	Non-fertilized	7.2 b	7.2 b	8.6 bc	6.0 b	10.8 b
	MESZ[b]	10.0 a	9.6 a	11.4 a	8.9 a	16.4 a
	LK[c]	6.0 b	6.0 b	7.8 c	5.3 b	8.9 b
	AP[d]	6.1 b	6.3 b	7.5 c	5.0 b	9.3 b
	All[e]	9.8 a	9.2 a	10.6 ab	8.3 a	17.5 a
	P > F	<0.01	<0.01	<0.01	<0.01	<0.01
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	4.7 c	5.2 c	5.2 c	5.4 c	6.7 c
	297,000	7.0 b	7.2 b	7.7 b	8.4 b	9.6 b
	445,000	9.9 a	10.3 a	10.9 a	11.9 a	13.3 a
	P > F	<0.01	<0.01	<0.01	<0.01	<0.01
	Fertilizer					
	Non-fertilized	7.3	8.0	9.3	9.0	10.5 ab
	MESZ	10.0	8.2	9.2	9.4	12.0 a
	LK	7.1	7.8	7.4	8.9	8.6 bc
	AP	5.9	6.3	6.3	7.0	7.3 c
	All	7.8	7.6	7.5	8.6	11.0 ab
	P > F	0.26	0.46	0.21	0.34	<0.01

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.24. Influence of soybean seeding rate and fertilizer application on irrigated and non-irrigated V4 N, P, K, S, and Zn partitioning to the leaves, Lansing, MI, 2019.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of V4 accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	86	76 a[a]	69	78 a	82
	297,000	86	74 ab	69	74 b	82
	445,000	85	71 b	66	72 b	81
	P > F	0.51	0.05	0.26	0.04	0.61
	Fertilizer					
	Non-fertilized	87 a	76 a	69	76	82
	MESZ[b]	84 c	71 c	67	74	81
	LK[c]	86 ab	74 ab	67	74	81
	AP[d]	86 ab	75 a	69	77	82
	All[e]	85 b	72 bc	67	74	82
	P > F	0.02	0.01	0.32	0.50	0.64
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	83	71	64	76 a	79
	297,000	82	70	62	74 ab	77
	445,000	83	70	62	72 b	79
	P > F	0.84	0.25	0.16	0.04	0.16
	Fertilizer					
	Non-fertilized	84	73 a	64	75	79
	MESZ	82	69 b	63	73	78
	LK	83	72 a	63	75	79
	AP	81	69 b	61	72	77
	All	82	69 b	62	74	78
	P > F	0.13	<0.01	0.29	0.14	0.63

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.25. Influence of soybean seeding rate and fertilizer application on irrigated and non-irrigated V4 N, P, K, S, and Zn partitioning to the leaves, Lansing, MI, 2020.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of V4 accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	81	70	56	78 a[a]	80
	297,000	80	67	52	75 b	78
	445,000	80	67	53	73 b	78
	P > F	0.49	0.14	0.17	0.07	0.42
	Fertilizer					
	Non-fertilized	80	67	54	75	77
	MESZ[b]	81	68	54	75	80
	LK[c]	81	68	54	75	79
	AP[d]	81	68	55	77	78
	All[e]	80	67	53	74	79
	P > F	0.40	0.97	0.95	0.70	0.30
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	83	70	63	78	80
	297,000	82	71	61	78	78
	445,000	82	71	63	79	81
	P > F	0.69	0.90	0.61	0.89	0.44
	Fertilizer					
	Non-fertilized	84	70	63	79	81
	MESZ	84	75	66	80	82
	LK	82	69	61	78	78
	AP	81	69	61	78	77
	All	81	71	64	77	80
	P > F	0.24	0.37	0.32	0.67	0.13

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.26. Influence of soybean seeding rate and fertilizer application on irrigated and non-irrigated V4 N, P, K, S, and Zn partitioning to the stems/petioles, Lansing, MI, 2019.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of V4 accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	14	24 b[a]	31	22 b	18
	297,000	14	26 ab	31	26 a	18
	445,000	15	29 a	34	28 a	19
	P > F	0.51	0.05	0.26	0.04	0.61
	Fertilizer					
	Non-fertilized	13 c	24 c	31	25	18
	MESZ[b]	16 a	29 a	33	26	19
	LK[c]	14 bc	26 bc	33	26	20
	AP[d]	14 bc	25 c	31	23	18
	All[e]	15 b	28 ab	33	26	18
	P > F	0.02	0.01	0.32	0.50	0.64
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	17	29 a	36	24 b	21
	297,000	18	30 a	38	26 ab	23
	445,000	17	30 a	38	28 a	21
	P > F	0.84	0.25	0.16	0.04	0.16
	Fertilizer					
	Non-fertilized	16	27 b	36	25	21
	MESZ	18	31 a	37	27	22
	LK	17	28 b	37	25	21
	AP	19	31 a	39	28	23
	All	18	31 a	38	26	22
	P > F	0.13	<0.01	0.29	0.14	0.63

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.27. Influence of soybean seeding rate and fertilizer application on irrigated and non-irrigated V4 N, P, K, S, and Zn partitioning to the stems/petioles, Lansing, MI, 2020.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of V4 accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	19	30	44	22 a[a]	20
	297,000	20	33	48	25 b	22
	445,000	20	33	47	27 b	22
	P > *F*	0.49	0.14	0.17	0.07	0.42
	Fertilizer					
	Non-fertilized	20	33	46	25	23
	MESZ[b]	19	32	46	25	20
	LK[c]	19	32	46	25	21
	AP[d]	19	32	45	23	22
	All[e]	20	33	47	26	21
	P > *F*	0.40	0.97	0.95	0.70	0.30
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	17	30	35	22	20
	297,000	18	29	39	22	22
	445,000	18	29	35	21	19
	P > *F*	0.69	0.90	0.61	0.89	0.44
	Fertilizer					
	Non-fertilized	16	30	35	21	19
	MESZ	16	25	34	20	18
	LK	18	31	39	22	22
	AP	19	31	39	22	23
	All	19	29	36	23	20
	P > *F*	0.24	0.37	0.32	0.67	0.13

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.28. Influence of seeding rate and fertilizer application on irrigated and non-irrigated R8 N, P, K, S, and Zn partitioning to the leaves, Lansing, MI, 2019.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	7.0	5.9	4.0	7.9	14
	297,000	7.3	6.5	4.8	8.9	14
	445,000	7.1	6.3	3.8	8.4	13
	P > F	0.91	0.76	0.19	0.50	0.78
	Fertilizer					
	Non-fertilized	7.0	6.1	4.3	8.2	13
	MESZ[a]	7.9	7.2	4.8	9.4	15
	LK[b]	6.6	5.4	3.9	7.7	12
	AP[c]	7.5	6.7	4.6	8.7	14
	All[d]	6.8	5.8	3.7	7.8	13
	P > F	0.58	0.37	0.31	0.45	0.33
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	6.1	5.9	3.2	7.8	16
	297,000	6.5	6.0	3.5	8.1	12
	445,000	6.4	5.8	3.0	8.2	12
	P > F	0.70	0.96	0.72	0.86	0.20
	Fertilizer					
	Non-fertilized	5.7	5.4	2.8	7.2	13
	MESZ	6.1	5.5	3.1	7.7	13
	LK	6.4	5.6	3.3	8.0	14
	AP	7.0	7.1	3.8	9.0	15
	All	6.4	6.0	3.1	8.2	14
	P > F	0.49	0.22	0.42	0.28	0.40

[a]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[b]LK: liquid potassium (0-0-28 N-P-K).
[c]AP: ammonium polyphosphate (10-34-0 N-P-K).
[d]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.29. Influence of seeding rate and fertilizer application on irrigated and non-irrigated R8 N, P, K, S, and Zn partitioning to the leaves, Lansing, MI, 2020.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	7.4	6.9	5.6	1.1	16
	297,000	8.9	7.7	5.8	1.2	21
	445,000	8.2	8.2	5.4	1.4	19
	P > F	0.59	0.70	0.89	0.40	0.34
	Fertilizer					
	Non-fertilized	8.6	8.0	6.3	1.3	17
	MESZ[b]	7.2	6.6	5.6	1.2	15
	LK[c]	8.4	8.0	6.4	1.2	21
	AP[d]	10.0	9.3	6.5	1.5	22
	All[e]	6.7	6.1	4.3	1.0	17
	P > F	0.18	0.22	0.18	0.28	0.27
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	7.4	6.1	2.8	1.2	23
	297,000	8.1	7.0	3.3	1.4	24
	445,000	8.1	7.2	3.4	1.4	24
	P > F	0.57	0.40	0.19	0.42	0.73
	Fertilizer					
	Non-fertilized	7.4	6.3	2.5 b[a]	1.3	22
	MESZ	7.1	6.1	2.7 b	1.4	21
	LK	7.6	6.5	3.8 a	1.1	24
	AP	7.8	6.8	3.0 b	1.3	24
	All	9.5	8.2	3.9 a	1.6	27
	P > F	0.18	0.28	<0.01	0.11	0.15

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.30. Influence of seeding rate and fertilizer application on irrigated and non-irrigated R8 N, P, K, S, and Zn partitioning to the stems/petioles, Lansing, MI, 2019.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	5.1	6.3	12.8	12	4.8
	297,000	4.2	4.9	10.8	11	4.2
	445,000	4.7	4.6	11.2	11	4.3
	P > F	0.18	0.14	0.40	0.55	0.26
	Fertilizer					
	Non-fertilized	3.9 b[a]	3.7 c	10.2 b	11 bc	3.7 b
	MESZ[b]	5.3 a	5.8 ab	10.9 b	13 a	5.1 a
	LK[c]	4.0 b	4.3 bc	11.3 b	10 c	4.0 b
	AP[d]	4.7 ab	5.8 ab	11.2 b	11 bc	4.1 b
	All[e]	5.4 a	6.6 a	14.5 a	12 ab	5.3 a
	P > F	0.01	0.02	0.09	0.04	0.03
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	4.0	3.5	4.2	5.9	3.5
	297,000	4.0	3.5	4.7	6.3	4.4
	445,000	4.4	3.9	4.5	5.9	4.4
	P > F	0.22	0.65	0.81	0.58	0.17
	Fertilizer					
	Non-fertilized	3.3 c	3.5	3.1 b	4.9 b	3.8
	MESZ	5.1 a	4.2	5.7 a	7.5 a	4.5
	LK	3.6 bc	3.2	5.6 a	4.7 b	3.6
	AP	3.8 bc	3.8	3.6 b	5.4 b	3.9
	All	4.2 ab	3.5	4.3 ab	7.0 a	4.6
	P > F	0.03	0.58	0.06	<0.01	0.30

[a]Least square means within each column followed by a common letter are not significantly different at α = 0.10.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.31. Influence of seeding rate and fertilizer application on irrigated and non-irrigated R8 N, P, K, S, and Zn partitioning to the stems/petioles, Lansing, MI, 2020.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	6.0 b[a]	9.1 b	19	19 b	6.2
	297,000	8.0 ab	11.4 ab	23	24 a	8.1
	445,000	9.8 a	13.2 a	22	23 a	8.9
	P > F	0.04	0.09	0.24	0.01	0.12
	Fertilizer					
	Non-fertilized	8.2	11.5	22	23 ab	8.3
	MESZ[b]	7.3	10.6	19	20 c	8.2
	LK[c]	7.6	10.2	22	21 bc	6.9
	AP[d]	9.2	12.9	22	24 a	8.2
	All[e]	7.6	11.0	20	22 abc	7.3
	P > F	0.37	0.50	0.69	0.09	0.50
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	4.8	5.9	6.5	6.9	5.1
	297,000	5.1	6.3	6.8	7.2	5.4
	445,000	5.0	5.8	6.5	6.6	5.2
	P > F	0.80	0.80	0.61	0.85	0.72
	Fertilizer					
	Non-fertilized	4.8	6.4	4.8 c	6.2 ab	4.9
	MESZ	4.9	5.8	5.3 bc	7.7 a	5.0
	LK	4.8	5.6	8.4 a	5.4 b	5.0
	AP	5.1	6.6	6.6 ab	6.4 ab	5.8
	All	5.3	5.7	6.9 a	8.8 a	5.5
	P > F	0.95	0.85	<0.01	0.05	0.41

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.32. Influence of seeding rate and fertilizer application on irrigated and non-irrigated R8 N, P, K, S, and Zn partitioning to the pods, Lansing, MI, 2019.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	4.8	4.2	21	8.2	6.6
	297,000	4.3	4.1	19	7.7	5.7
	445,000	4.1	3.6	19	7.4	5.4
	P > F	0.28	0.53	0.13	0.37	0.15
	Fertilizer					
	Non-fertilized	4.1	3.6	18	7.6	5.9
	MESZ[b]	4.6	4.0	19	7.9	5.8
	LK[c]	4.0	3.6	20	7.2	5.8
	AP[d]	4.5	4.4	19	7.8	5.9
	All[e]	4.7	4.2	22	8.2	6.3
	P > F	0.53	0.65	0.18	0.70	0.96
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	3.4	3.3	12.1	4.3	4.2
	297,000	4.3	3.6	11.6	4.2	4.4
	445,000	2.8	2.4	9.2	3.2	3.2
	P > F	0.38	0.47	0.11	0.40	0.39
	Fertilizer					
	Non-fertilized	3.4	3.0	8.6 c[a]	3.8	3.9
	MESZ	3.4	3.5	12.6 ab	4.4	4.4
	LK	3.3	2.7	13.7 a	3.6	3.7
	AP	3.8	3.2	9.8 c	3.9	4.0
	All	3.6	3.0	10.2 bc	3.8	3.9
	P > F	0.93	0.84	0.02	0.88	0.88

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.33. Influence of seeding rate and fertilizer application on irrigated and non-irrigated R8 N, P, K, S, and Zn partitioning to the pods, Lansing, MI, 2020.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	4.5 b[a]	5.4 b	18	6.2 b	5.5 b
	297,000	5.2 ab	6.6 a	22	7.6 a	6.4 ab
	445,000	5.8 a	7.3 a	18	6.7 ab	7.3 a
	P > F	0.06	0.05	0.11	0.07	0.05
	Fertilizer					
	Non-fertilized	5.6	7.1	21	7.2	6.9
	MESZ[b]	4.9	6.1	19	7.0	6.7
	LK[c]	4.7	5.8	17	6.1	5.8
	AP[d]	5.4	6.8	20	7.2	6.5
	All[e]	5.3	6.3	19	6.7	6.3
	P > F	0.51	0.36	0.48	0.39	0.49
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	6.8	6.8	24 a	7.7 a	7.5 a
	297,000	6.7	6.4	24 a	7.7 a	7.3 a
	445,000	5.4	5.1	19 b	5.8 b	5.5 b
	P > F	0.21	0.15	0.10	0.08	0.09
	Fertilizer					
	Non-fertilized	6.1	6.0	19 b	6.7	6.6
	MESZ	5.7	5.5	19 b	6.2	6.5
	LK	6.0	5.9	24 a	6.7	6.2
	AP	6.8	6.6	25 a	8.2	7.7
	All	7.0	6.6	24 a	7.5	6.8
	P > F	0.61	0.74	0.04	0.26	0.60

[a]Least square means within each column followed by a common letter are not significantly different at α = 0.10.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.34. Influence of seeding rate and fertilizer application on irrigated and non-irrigated R8 N, P, K, S, and Zn partitioning to the grain, Lansing, MI, 2019.

Site	Treatment	N	P	K	S	Zn
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	84	84	62	72	75
	297,000	84	85	66	73	76
	445,000	84	86	66	73	78
	P > *F*	0.66	0.51	0.26	0.84	0.51
	Fertilizer					
	Non-fertilized	85	87	66	74	78
	MESZ[b]	82	83	65	70	74
	LK[c]	86	87	65	76	78
	AP[d]	83	83	66	73	76
	All[e]	83	83	60	72	76
	P > *F*	0.21	0.14	0.26	0.16	0.43
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	87	87	82	83	77
	297,000	85	87	80	81	78
	445,000	86	88	83	83	80
	P > *F*	0.44	0.74	0.28	0.71	0.21
	Fertilizer					
	Non-fertilized	88	88	88 a[a]	85 a	80
	MESZ	86	87	79 cd	81 c	79
	LK	87	88	78 d	84 ab	78
	AP	85	86	83 b	82 bc	77
	All	86	88	82 bc	81 bc	78
	P > *F*	0.34	0.38	<0.01	0.10	0.69

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.35. Influence of seeding rate and fertilizer application on irrigated and non-irrigated R8 N, P, K, S, and Zn partitioning to the grain, Lansing, MI, 2020.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		Percent (%) of total accumulation				
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	82	79	57	67 a[a]	72
	297,000	78	74	49	59 b	65
	445,000	76	71	55	61 b	65
	P > F	0.16	0.13	0.13	0.04	0.13
	Fertilizer					
	Non-fertilized	78	74	51	61	68
	MESZ[b]	81	77	57	65	70
	LK[c]	79	76	54	64	66
	AP[d]	75	71	51	58	63
	All[e]	81	77	56	64	70
	P > F	0.14	0.30	0.44	0.14	0.54
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	81	81	67	76	65
	297,000	78	80	67	75	64
	445,000	81	82	71	76	65
	P > F	0.39	0.68	0.38	0.72	0.84
	Fertilizer					
	Non-fertilized	82	81	74 a	77	66
	MESZ	82	83	73 a	76	67
	LK	81	82	64 b	77	64
	AP	78	80	67 b	75	63
	All	78	79	65 b	72	61
	P > F	0.30	0.71	0.02	0.40	0.32

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.36. Irrigated and non-irrigated soybean grain nutrient concentration at physiological maturity (R8) as affected by seeding rate and fertilizer application, Lansing, MI, 2019.

Site	**Treatment**	**N**	**P**	**K**	**S**	**Zn**
		———	——— $g\ kg^{-1}$ ———			$mg\ kg^{-1}$
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	65 b[a]	5.9	19	3.1 b	35
	297,000	66 a	5.9	19	3.2 a	34
	445,000	66 a	5.9	19	3.2 a	35
	P > F	0.05	0.89	0.42	0.02	0.41
	Fertilizer					
	Non-fertilized	65 b	5.6 c	19 b	3.1 b	35
	MESZ[b]	67 a	5.9 bc	19 b	3.2 a	35
	LK[c]	66 b	5.8 c	19 b	3.2 a	35
	AP[d]	65 b	6.0 ab	19 b	3.1 b	34
	All[e]	65 b	6.1 a	20 a	3.2 a	35
	P > F	0.01	<0.01	<0.01	<0.01	0.58
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	63	5.7	18	3.1 a	38
	297,000	64	5.6	18	3.0 b	39
	445,000	64	5.5	18	2.9 b	38
	P > F	0.43	0.48	0.47	<0.01	0.70
	Fertilizer					
	Non-fertilized	64 ab	5.5	18	3.0	38
	MESZ	63 b	5.5	18	3.0	38
	LK	62 c	5.6	18	2.9	38
	AP	64 ab	5.7	18	3.0	39
	All	65 a	5.6	18	3.0	39
	P > F	<0.01	0.81	0.17	0.35	0.97

[a]Least square means within each column followed by a common letter are not significantly different at α = 0.10.

[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

[c]LK: liquid potassium (0-0-28 N-P-K).

[d]AP: ammonium polyphosphate (10-34-0 N-P-K).

[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.37. Irrigated and non-irrigated soybean grain nutrient concentration at physiological maturity (R8) as affected by seeding rate and fertilizer application, Lansing, MI, 2020.

Site	Treatment	N	P	K	S	Zn
		g kg^{-1}				mg kg^{-1}
Irrigated	Seeding rate, seeds ha^{-1}					
	148,000	57	5.6	21	3.3	37
	297,000	58	5.7	21	3.4	39
	445,000	58	5.7	21	3.4	38
	P > F	0.13	0.55	0.80	0.13	0.34
	Fertilizer					
	Non-fertilized	58	5.6	21	3.4	36
	MESZ[b]	58	5.7	21	3.4	38
	LK[c]	58	5.7	21	3.4	38
	AP[d]	58	5.6	21	3.3	39
	All[e]	56	5.7	21	3.4	40
	P > F	0.48	0.55	0.11	0.19	0.17
Non-irrigated	Seeding rate, seeds ha^{-1}					
	148,000	56 b[a]	5.4	19	2.8	42
	297,000	57 ab	5.3	19	2.7	41
	445,000	58 a	5.2	19	2.7	42
	P > F	0.07	0.28	0.22	0.18	0.35
	Fertilizer					
	Non-fertilized	57 b	5.3	19	2.6 c	41 c
	MESZ	58 a	5.2	19	2.8 b	42 b
	LK	57 b	5.2	20	2.6 c	39 d
	AP	57 b	5.4	19	2.6 c	41 c
	All	57 b	5.3	19	3.0 a	44 a
	P > F	0.02	0.21	0.11	<0.01	<0.01

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

[c]LK: liquid potassium (0-0-28 N-P-K).

[d]AP: ammonium polyphosphate (10-34-0 N-P-K).

[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.38. Impact of soybean seeding rate and fertilizer application on irrigated and non-irrigated nodule count, stem diameter, and pod count, Lansing, MI, 2019.

Site	Treatment	Nodule count	Stem diameter	Pod count
		nodules plant^{-1}	———mm———	pods ha^{-1}
Irrigated	Seeding rate, seeds ha^{-1}			
	148,000	69	8.6 a[a]	13333362
	297,000	64	6.3 b	11917302
	445,000	55	5.5 c	13554528
	P > F	0.16	<0.01	0.33
	Fertilizer			
	Non-fertilized	58	6.4 c	12273464 b
	MESZ[b]	63	7.3 b	13077904 ab
	LK[c]	61	6.2 c	11879669 b
	AP[d]	67	6.1 c	12441330 b
	All[e]	64	8.0 a	15002954 a
	P > F	0.76	<0.01	0.07
Non-irrigated	Seeding rate, seeds ha^{-1}			
	148,000	30	7.0 a	8501695
	297,000	30	5.3 b	9278077
	445,000	28	4.6 c	8349424
	P > F	0.79	<0.01	0.34
	Fertilizer			
	Non-fertilized	26	5.2 b	8231339
	MESZ	30	6.1 a	9322920
	LK	27	5.3 b	8551868
	AP	33	5.4 b	8478381
	All	31	6.1 a	8964153
	P > F	0.48	<0.01	0.68

[a]Least square means within each column followed by a common letter are not significantly different at α = 0.10.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.39. Impact of soybean seeding rate and fertilizer application on irrigated and non-irrigated nodule count, stem diameter, and pod count, Lansing, MI, 2020.

Site	Treatment	Nodule count	Stem diameter	Pod count
		nodules plant^{-1}	——mm——	pods ha^{-1}
Irrigated	Seeding rate, seeds ha^{-1}			
	148,000	107	12.0 a[a]	10824875
	297,000	83	9.2 b	12330637
	445,000	70	7.4 c	10329499
	P > F	0.12	<0.01	0.42
	Fertilizer			
	Non-fertilized	88	9.1	12396055
	MESZ[b]	85	10.2	10127732
	LK[c]	91	9.3	11032240
	AP[d]	87	9.5	10759793
	All[e]	82	9.6	11492532
	P > F	0.75	0.20	0.65
Non-irrigated	Seeding rate, seeds ha^{-1}			
	148,000	35	10.5 a	11121083
	297,000	32	7.8 b	13813216
	445,000	29	5.9 c	11506068
	P > F	0.31	<0.01	0.13
	Fertilizer			
	Non-fertilized	33	7.4 c	11553662
	MESZ	35	8.3 b	11823999
	LK	28	7.8 b	12514562
	AP	31	7.7 bc	13241071
	All	34	9.1 a	11600651
	P > F	0.48	<0.01	0.80

[a]Least square means within each column followed by a common letter are not significantly different at α = 0.10.
[b]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[c]LK: liquid potassium (0-0-28 N-P-K).
[d]AP: ammonium polyphosphate (10-34-0 N-P-K).
[e]All: combination of MESZ, LK, and AP fertilizer applications.

Table 2.40. Irrigated white mold incidence, white mold severity, and lodging as influenced by soybean seeding rate and fertilizer application, Lansing, MI, 2020.

Treatment	**Incidence**	**Severity**[a]	**Lodging**[b]
	———%———	———0-3———	———0-5———
Seeding rate, seeds ha^{-1}			
148,000	20 a[a]	0.6 a	1.6 a
297,000	21 a	0.8 a	2.1 a
445,000	22 a	0.8 a	2.8 a
P > F	0.37	0.26	0.42
Fertilizer			
Non-fertilized	23 a	0.7 a	1.6 a
MESZ[c]	20 a	1.1 a	2.3 a
LK[d]	22 a	0.7 a	2.5 a
AP[e]	20 a	0.6 a	2.4 a
All[f]	20 a	0.8 a	2.0 a
P > F	0.31	0.12	0.95

[a]White mold severity rated using a scale of 0 = no symptoms and 3 = lesions on main stem resulting in poor pod fill or plant death.
[b]Lodging rated using a scale of 0-5 where 0 = no lodging and 5 = plants completely lodged
[c]MESZ: MicroEssential SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).
[d]LK: liquid potassium (0-0-28 N-P-K).
[e]AP: ammonium polyphosphate (10-34-0 N-P-K).
[f]All: combination of MESZ, LK, and AP fertilizer applications.

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CHAPTER 3

NITROGEN AND SULFUR RESPONSES OF DRY BEAN IN MICHIGAN

Abstract

Greater dry bean (*Phaseolus vulgaris* L.) yield and a potential decrease in soil sulfur (S) supply has practitioners questioning whether nitrogen (N) and sulfur fertilizer response in dry bean has increased. Three multi-year trials were established in Michigan to evaluate nitrogen rate, sulfur rate, and sulfur source on dry bean growth and grain yield. Four dry bean varieties responded similarly to N rate, S rate, and S source across all site-years. Compared to applying no N, ≥ 60 lb N/acre increased dry matter accumulation up to 46 and 54%, but grain yield was not significantly influenced by N rate. S application did not significantly increase grain yield regardless of rate or source as implied by lack of S deficiency symptoms, adequate S concentration in the uppermost trifoliate, and SOM (soil organic matter) levels between 2.4 and 2.6%. The data suggest the likelihood of a grain yield response from supplemental S application may be dependent on site-specific factors and soil properties. Although N application did not benefit dry bean grain yield, the influence unpredictable weather has on N supply and demand combined with a short growing season (i.e., 85 to 100 d) may justify to some extent N application to protect yield potential. However, excess N applications can reduce nodulation and increase risk for disease and N loss to the environment.

Introduction

Michigan ranks second in total U.S. dry bean production (6,033,000 cwt) generating more than US$185 million (USDA NASS, 2020) with black bean, navy bean, and small red bean the top major market classes (USDA NASS, 2020). Production acres are focused in the northeastern Saginaw Valley region where loam and clay soils dominate and growers typically plant anywhere from 85 to 100 d maturity beans during June with harvest in September. From 2000 to 2020, average grain yield of black, navy, and small red increased by 51, 59, and 67%, respectively (USDA NASS, 2020). Increases in grain yield potential may partially be due to the genetic advancement of dry bean varieties (e.g., disease resistance and stress tolerance) but practitioners are also questioning whether the response to N application has changed in modern dry bean production system. Unlike corn, wheat, or other N responsive crops, dry bean fix atmospheric N and convert it into a plant usable form through a symbiotic relationship with *Rhizobium* bacteria (Adams et al., 2016). George and Singleton (1992) observed the percentage of plant N derived from N fixation at physiological maturity (R7) when N fertilizer was applied at a rate of 8 lb N/acre ranged from 32-69% and 16-18% for soybean (*Glycine max L*. Merr.) and dry bean, respectively. Thus, dry bean is considered a relatively poor N fixer and often requires supplemental N fertilization in addition to soil N contributions (i.e., residual N and mineralized N) for optimal plant growth and yield (Mckenzie et al., 2000; Farid et al., 2016). Yield increases from N fertilization may generally occur on N-poor soils (i.e., low residual N with low SOM) but are also dependent on crop rotation, agronomic practices, organic amendments, and environmental conditions (Westermann et al., 1981). Current university guidelines recommend the application of 40-60 lb N/acre, but yield increases from N fertilization over the past 30 years were generally inconsistent (Warncke et al., 2009). Moraghan et al. (1991) found the application of N fertilizer had no effect or decreased navy bean yield at three of four locations while Eckert et al. (2011) reported no yield increase to N fertilization across three pinto bean cultivars. However, under low residual soil NO_3-N concentrations, Blaylock (1995) reported a yield increase across varying N levels and Soratto et al. (2014) found N application increased early-season plant growth and reduced plant mortality later concluding N fertilizer was important for dry bean establishment. Despite potential benefits to N fertilizer application, additional risk from over-application exists in the form of reduced N fixation, delayed maturity, increased white mold (caused by *Sclerotinia sclerotiorum*) disease due to greater canopy density, and increased risk for environmental N losses (Warncke et al., 2009; Eckert et al., 2011; Argraw and Akuma, 2015; Akter et al., 2018).

Sulfur has not been recommended in Michigan dry bean production due to sufficient soil S supply or S carryover from application to other N-responsive crops within the dry bean rotation including wheat (*Triticum aestivum* L.), sugarbeet (*Beta vulgaris* L.), and corn (*Zea mays* L.) (Warncke et al., 2009). Sulfur deficiencies have increased due to an 85% decrease in atmospheric S deposition in Michigan between 1980 and 2019, greater usage of concentrated fertilizers containing little or no S. and increased S removal from greater biomass production and grain yields (McGrath and Zhao, 1995; Chien et al., 2009; National Atmospheric Deposition Program, 2019). Hitsuda et al. (2005) suggested that S application at early growth stages should be considered to provide sufficient S supply throughout the growing season as developing roots cannot access S accumulated deeper in the soil profile. However, S mineralization increases with soil temperatures between 68 to 104ºF (Havlin et al., 2014), and in the current study warm soil temperatures (64-68ºF) at dry bean planting (i.e., June) indicate the potential for S mineralization to satisfy dry bean S requirements. The probability of an S response in dry bean may be site-specific depending upon SOM, residual soil S, and crop rotation as observed in other crops including soybean (Kaiser and Kim, 2013). However, soil S analysis may not be a reliable indicator of grain yield responses to S application as S concentration varies considerably between different soil horizons thus plant analysis may be a better diagnostic tool for identifying S sufficiency (Sawyer and Barker, 2002; Hitsuda et al., 2005; Culman et al., 2020). Glowacka et al. (2019) observed a 14.5% yield increase and improved grain quality from S application prior to planting, thus concluding S fertilization should be included in dry bean crop management. In a review of dry bean responses to S fertilization, Pias et al. (2019) found 50% (n=6) of dry bean trials increased grain yield by 12% in response to S application when the concentration of soil available SO_4-S was below critical. Conversely, Nascente et al. (2017b) found six different dry bean cultivars did not differ in grain yield response to S fertilizer application. Apart from grain yield and quality, S application may potentially impact nodulation in dry bean because legumes that acquire N through BNF typically have a greater S requirement than legumes which only use soil N (Sulieman et al., 2013). Nascente et al. (2017a) found S application between 0-54 lb S/acre did not influence the number of nodules or dry mass of nodules per root. Although S plays a significant role in N assimilation by N fixing bacteria (Pacyna et al., 2006), few data exist examining S application on nodulation in dry bean.

Sulfur fertilizers often contain either SO_4-S, elemental S, or a combination of the two (SO_4-S and elemental S). Applied prior to planting, SO_4-S fertilizer is readily available as compared to elemental S which must be oxidized to SO_4-S through microbial activity prior to plant uptake (Boswell and Friesen, 1993). Oxidation to convert elemental sulfur into SO_4-S is slow and depends upon soil environmental conditions (i.e., temperature and moisture) suitable for aerobic microbial activity (Havlin et al., 2014). However, under leaching conditions the total recovery of elemental S over an extended period (i.e., five years) may reach or surpass SO_4-S (Degryse et al., 2021). Combined with the long-term S availability from the slow oxidation of elemental S and a lower potential for short-term losses, elemental S offers the potential to reduce future S deficiencies associated with uncertain soil S availability (Goyal et al., 2021). Although a combination of both SO_4-S and elemental S may be useful to provide both immediate and long-term S availability (Norton et al. 2013), grain yield response to elemental S or combined (SO_4-S and elemental S combinations) has been inconsistent. Across laboratory, greenhouse, and field studies concerning S fertilizer sources, Chien et al. (2016) concluded granular fertilizers containing elemental S or a combination of elemental S and SO_4-S provide less available S during the first growing season after fertilizer application as compared to traditional SO_4-S fertilizer sources. However, in soybean, Purucker and Steinke (2020) discovered the application of a combined (SO_4-S and elemental S) fertilizer increased grain S accumulation 8% compared to the non-fertilized control possibly due to late-season S availability and uptake from elemental S oxidation.

Continued yield improvements in modern dry bean varieties and increased crop (i.e., corn, wheat, and sugarbeet) responses from S application in Michigan necessitate a greater understanding of how N and S fertilizer application impact dry bean. The objective of this study was to 1) evaluate the effect of N application rates across multiple dry bean varieties on grain yield, dry matter accumulation, and root nodulation and -2) evaluate S fertilizer rate and source effects across dry bean varieties for grain yield and root nodulation.

Materials and Methods

Location and Site Description

Nitrogen rate, sulfur rate, and sulfur source field studies were conducted in 2019 and 2020 at the Michigan State University Saginaw Valley Research and Extension Center near Richville, MI (43°23’57.3”N, 83°41’49.7”W) on a non-irrigated Tappan-Londo loam soil (fine-loamy, mixed, active, calcareous, mesic Typic Enduaquolls). Soil samples collected prior to fertilizer application to an 8-inch depth were analyzed for pH (1:1 soil/water), cation exchange capacity (CEC), soil organic matter (SOM) (loss on ignition), P (Bray-P1), K (ammonium acetate extractable K), and S (0.25 M KCL); and to a 1-ft depth for NO_3-N (cadmium reduction) (Table 3.01). All sites were previously cropped to corn and were either fall chisel or moldboard plowed (9-inch depth) followed by two passes of a soil finisher (3-inch depth) prior to planting. Full season pest control followed Michigan State University best management practices. Environmental data were collected using the Michigan State University Enviro-weather (https://enviroweather.msu.edu, Michigan State University, East Lansing, MI). Temperature and precipitation 30-year means were obtained from the National Oceanic and Atmosphere Administration (NOAA, 2019).

Experimental Design and Procedures for N rate

Studies were arranged as a randomized complete split-plot design with four replications. The main plot factor was dry bean variety and the subplot factor was N rate. Varieties consisted of 'Zenith' black bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine); 'Black Bear' black bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine); 'Viper' small red bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine); and 'Merlin' navy bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine). Six N rates (0, 30, 60, 90, 120, and 150 lb N/acre) were broadcast as urea (46-0-0 N-P-K) and incorporated prior to planting (3-inch depth) on 18 June 2019 and 04 June 2020, respectively. Individual 4-row plots measured 15-ft in length and 7-ft in width. Dry beans were planted using a White 6000 series planter (AGCO Corp., Duluth, GA) at a base seeding rate of 144,000 seeds/acre in 20-inch rows on 19 June 2019 and 04 June 2020.

Post-harvest NO_3-N was collected from three soil cores (1-ft depth) in the center two rows of each plot. Nodules were counted six weeks after emergence from five consecutive plants/plot. Leaf nutrient analysis was collected from the uppermost fully developed trifoliate of 20 plants/plot. Aboveground plant biomass was sampled from five consecutive plants/plot when at least 50% of the crop achieved the R5 growth stage. Dry weight was determined by drying plant tissue at 150°F to approximately 0% moisture. White mold incidence was calculated by rating thirty consecutive plants/plot for disease infection at maturity (R8). Grain yield, moisture, and test weight were determined by direct harvesting the center two rows of each plot with a Wintersteiger Quantum research combine (Winterstieger AG, Austria). Final grain yields were corrected to 18% moisture. Economic return was calculated using an average local cash price of $30.00, $32.00, and $32.00/cwt for black, navy, and small red bean, respectively, and input costs of $0.45 lb N for urea. Fertilizer application costs of $5.22/acre were estimated for the prior to planting broadcast application using Michigan State University Extension Custom Machine and Work Rate Estimates (Stein, 2019). Net economic return was calculated using a partial budget subtracting input cost from gross revenue (i.e., grain price multiplied by yield).

Experimental Design and Procedures for S rate

Studies were arranged as a randomized complete split-plot design with four replications. The main plot factor was dry bean variety and the subplot factor was S rate. Varieties consisted of 'Zenith' black bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine); 'Black Bear' black bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine); 'Viper' small red bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine); and 'Merlin' navy bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine). Four S rates (0, 25, 50, and 100 lb S/acre) were broadcast as gypsum (0-0-0-23-18 N-P-K-Ca-S) and incorporated prior to planting (3-inch depth) on 18 June 2019 and 04 June 2020, respectively. All plots received 60 lb N/acre using urea (46-0-0 N-P-K) with S application before planting. Individual 4-row plots measured 15-ft in length and 7-ft in width. Dry beans were planted using a White 6000 series planter (AGCO Corp., Duluth, GA) at a base seeding rate of 144,000 seeds/acre in 20-inch rows on 19 June 2019 and 04 June 2020.

Nodules were counted six weeks after emergence from five consecutive plants/plot. Leaf nutrient analysis was collected from the uppermost fully developed trifoliate of 20 plants/plot. Grain yield, moisture, and test weight were determined by direct harvesting the center two rows of each plot with a Wintersteiger Quantum research combine (Winterstieger AG, Austria). Final grain yields were corrected to 18% moisture. Economic return was calculated using an average local cash price of $30.00, $32.00, and $32.00/cwt for black, navy, and small red bean, respectively, and input costs of $0.14 lb S for gypsum. Fertilizer application costs of $5.22/acre were estimated for the prior to planting broadcast application using Michigan State University Extension Custom Machine and Work Rate Estimates (Stein, 2019). Net economic return was calculated using a partial budget subtracting input cost from gross revenue (i.e., grain price multiplied by yield).

Experimental Design and Procedures for S source

Studies were arranged as a randomized complete split-plot design with four replications. The main plot factor was dry bean variety and the subplot factor was S fertilizer source. Varieties consisted of ‘Zenith’ black bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine); ‘Black Bear’ black bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine); ‘Viper’ small red bean (ADM Seedwest, Decatur, IL), a Type II (upright indeterminate short vine); and ‘Merlin’ navy bean (ADM Seedwest, Decatur, IL), a

Type II (upright indeterminate short vine). Gypsum (0-0-0-23-18 N-P-K-Ca-S), ammonium sulfate (AS) (21-0-0-24 N-P-K-S), and MicroEssentials® SZ® (MESZ) (Mosaic CO., Plymouth, MN) (12-40-0-10-1 N-P-K-S-Zn) were broadcasted and incorporated prior to planting (3-inch depth) at a rate of 25 lb S/acre on 18 June 2019 and 04 June 2020, respectively. All plots were balanced to receive 60 lb N/acre using urea (46-0-0 N-P-K) with S application before planting. Individual 4-row plots measured 15-ft in length and 7-ft in width. Dry beans were planted using a White 6000 series planter (AGCO Corp., Duluth, GA) at a base seeding rate of 144,000 seeds/acre in 20-inch rows on 19 June 2019 and 04 June 2020.

Nodules were counted six weeks after emergence from five consecutive plants/plot. Leaf nutrient analysis was collected from the uppermost fully developed trifoliate of 20 plants/plot. Grain yield, moisture, and test weight were determined by direct harvesting the center two rows of each plot with a Wintersteiger Quantum research combine (Winterstieger AG, Austria). Final grain yields were corrected to 18% moisture. Economic return was calculated using an average local cash price of $30.00, $32.00, and $32.00/cwt for black, navy, and small red bean, respectively, and input costs of $0.45 lb N, $0.14 lb S, $0.77 lb S, and $2.95 lb S for urea, gypsum, AMS, and MESZ fertilizer treatments, respectively. Fertilizer application costs of $5.22/acre were estimated for the prior to planting broadcast application using Michigan State University Extension Custom Machine and Work Rate Estimates (Stein, 2019). Net economic return was calculated using a partial budget subtracting input cost from gross revenue (i.e., grain price multiplied by yield).

Statistical Analyses

Statistical analyses were performed using PROC GLIMMIX in SAS 9.4 (SAS Institute, 2012) at $\alpha = 0.10$. Site-year, variety, and fertilizer application were considered fixed effects and the replication as random. Normality of residuals were examined using the UNIVARIATE procedure ($P \leq .05$). Squared and absolute values of residuals were examined with Levene's Test to confirm homogeneity of variances ($P \leq .05$). Least square means were separated using the LINES option of the slice statement when ANOVA indicated a significant interaction ($P \leq .10$). Pearson product-moment correlations were derived using the REG procedure of SAS to investigate the relationship between dry matter accumulation, grain yield, and white mold incidence.

Results and Discussion

Environmental Conditions

Cumulative 2019 and 2020 growing season (June-September) precipitation was 4% greater and 21% below 30-yr averages, respectively (Table 3.02). Above average 2019 precipitation occurred soon after planting resulting in soil crusting and greater incidence of soil-borne disease (i.e., *Fusarium solani* and *Rhiozoctonia solani* root rot) which may have limited vegetative and root growth, nodulation, yield, and response to N and S application. Optimal spring 2020 planting conditions and normal summer precipitation patterns resulted in greater yields than 2019. Growing season air temperatures were within 5% of the 30-yr average across both years.

Dry Bean Response to Nitrogen Rate

Across site years N rate did not significantly impact V2 plant stand (data not shown). Sorrato et al. (2014) found N application improved the establishment of dry bean when N was applied pre-sowing in a no-till system due to greater initial plant growth and a reduction in plant mortality during early vegetative stages. However, dry bean does not tolerate N fertilizer to be placed with the seed at planting as salt injury may decrease plant population (Warncke et al., 2009). Thus, the potential to reduce plant stand at early vegetative stages may also exist for high rates of pre-plant and incorporated N (i.e., > 90 lb N/acre) prior to planting. Two inches of rain two days after 2019 planting and one inch of rain six days after 2020 planting may have mitigated risk for salt injury by solubilizing and moving N out of the immediate germination zone (Steinke and Bauer, 2017). Although plant stand reductions did not occur in the current study, growers should use caution when applying high N rates (i.e., > 90 lb N/acre) prior to or at-planting due to potential saltation.

Tissue R1 uppermost trifoliate N concentration was significantly ($P < 0.01$) affected by N rate in both years but not variety-specific (Table 3.03). Compared to no N, 120 lb N/acre increased N concentration in the uppermost trifoliate 18 and 10% in 2019 and 2020, respectively, suggesting greater N availability due to N application likely resulted in increased tissue N uptake. Previous studies found the application of N increased dry bean tissue N concentration (Liebman et al., 1995; Sorratto et al., 2014), and according to Ambrosano et al. (1997), leaf N concentrations between 3.0-5.0% were considered adequate for optimal growth, thus there was no indication of early-season N deficiencies in the current study.

Nodulation numbers ranged between 0.9-4.3 and 3.7-7.9 nodules plant^{-1} across N rates in 2019 and 2020, respectively (Table 3.03). Dry soil conditions (i.e., 10% below the 30-yr average) during July and August 2019 likely reduced nodulation compared to 2020 (Kumarasinghe et al., 1992). However, other environmental factors may influence nodulation including pH, salinity, soil temperature, and P availability (Farid et al., 2016). Nodulation was not affected up to 60 lb N/acre in 2020 with significant decreases at rates > 60 lb N/acre. Results in 2020 agree with Argraw and Akuma (2015) who reported decreased nodulation with increased rates of N fertilizer. Nodulation was significantly affected by variety (*P* = 0.06) and N rate (*P* = 0.06) in 2020. Previous research suggested plant nodulation varies between dry bean genotypes and varieties thus impacting response to applied N (Wolyn et al., 1991; Fageria et al., 2013). Compared to the black bean varieties ‘Zenith’ and ‘Black Bear’, the navy bean variety ‘Merlin’, produced 3.5 and 3.4 fewer nodules plant^{-1}, respectively.

Aboveground R5 dry matter was significantly affected by N rate ($P \leq 0.01$) across years (Table 3.04). At N application rates from 0-150 lb N/acre, aboveground dry matter ranged from 3650 to 5314 lb/acre and 4355 to 6687 lb/acre in 2019 and 2020, respectively. Reduced 2019 aboveground dry matter production was the result of below average precipitation (i.e., less than 10% of 30-yr average) during July and August. Biomass production significantly increased up to 60 lb N/acre with no observed differences at N rates > 60 lb N/acre. Lack of plant height differences suggests additional aboveground production was likely the result of greater canopy density (Table 3). However, growers should be aware to not confuse greater in-season biomass production with increased grain yield. Results agree with previous research observing increased dry matter production following N application (Moraghan et al., 1991; George and Singleton, 1992). However, Edje et al. (1975) found dry matter production peaked at 107 lb N/acre and decreased thereafter when evaluating N rates between 0-178 lb N/acre. Since 1975, dry bean varieties have shifted from a Type III (indeterminate prostrate) to a Type II (indeterminate upright) growth habit partially due to greater harvestability (Soltani et al., 2016). Compared to Type II, type III plants are more vulnerable to disease and lodging due to dense canopy cover and weaker main stems unable to support branches and pods. Through improvements in plant canopy architecture, grain yield has simultaneously increased during this same time due in part to greater N use efficiency and N fixation as modern dry bean varieties may potentially require less N than older varieties (Fageria and Santos, 2008; Akter et al., 2017; Heilig et al., 2017). In contrast to Edje et al. (1975), aboveground dry matter production peaked at a much lower N rate (60 lb N/acre) with no significant decreases in dry matter beyond 60 lb N/acre in the current study. Findings suggest the possibility that modern dry bean varieties may require less N compared to older varieties partially due to improvements in breeding.

Precipitation that was 3-6% above 30-yr averages in July and August 2020 coupled with cool September air temperatures and dense canopy biomass may have provided favorable conditions for white mold (caused by *Sclerotinia sclerotiorum*). White mold did not occur in 2019 potentially due to a low number of sclerotia within the field tested and unfavorable environmental conditions limiting biomass production, canopy development, apothecia production, and plant infection. White mold incidence was significantly influenced by N rate ($P = 0.02$) and variety ($P = < 0.01$) in 2020 (Table 3.04). The small red bean variety ‘Viper’ increased white mold incidence up to 73% compared to the black bean varieties ‘Zenith’ and ‘Black Bear’ and 52% compared to the navy bean variety ‘Merlin’. Although ‘Viper’ is classified as a Type II (indeterminate upright short vine) variety, visual observations suggest ‘Viper’ may potentially be more prone to a closed canopy and sclerotinia infection due to a greater vining growth habit compared to ‘Zenith’, ‘Black Bear’, and ‘Merlin’ (Schwartz et al., 1978). However, white mold incidence and severity in commercially acceptable varieties is not solely dependent on plant architectural traits but instead a combination of physiological resistance and plant architectural traits (Schwartz et al., 1987). White mold incidence increased with N application greater than 60 lb N/acre and appeared to coincide with aboveground dry matter production. Thus, growers should take caution not to over apply N as stimulated foliage growth can create a favorable microenvironment for white mold disease and reduce grain yield potential (Miklas et al., 2013). Additional cultural practices including row spacing, seeding rate, irrigation, and variety selection may affect white mold disease risk and should be considered prior to making N management decisions (Coyne et al., 1974; Schwartz et al., 1987; Kolkman and Kelly, 2002; Ando et al., 2007).

Nitrogen rate and variety did not interact to affect grain yield indicating N application rates do not require adjustments solely based on variety (Table 3.05). Similar grain yield results were obtained in Alberta, where four commercial dry bean varieties (i.e., great northern, small red, pinto, and pink bean) under irrigation did not interact with N application rates (Mckenzie et al., 2000). Westermann et al. (1981) found more than half of total N uptake occurred during vegetative growth in which N fixation may be inadequate to satisfy plant N demand, suggesting that soil-derived N (i.e., residual soil N and mineralized N) and N fertilizer may be critical components for early-season N requirements (George and Singleton, 1992). However, in addition to varying rates of plant N demand from year to year, estimating N supply from N fixation and soil-derived N sources is difficult in part due to 1) by nature the environment is random and 2) biological processes (i.e., N mineralization and N fixation) which influence N supply are independent (Raun et al., 2019). These uncertainties create ambiguity when attempting to predict the correct amount of N fertilizer to apply prior to planting without also reducing the N fixation capabilities of the plant. The application of N prior to planting can help account for environmental variability and may affect grain yield more so than N applied after emergence. However, unless N fixation and soil-derived N supply cannot meet plant N requirements, the likelihood of a grain yield response to N application may be low (Sorrato et al., 2013; Sorrato et al., 2014). In both years residual soil NO_3-N measured 18 lb NO_3-N/acre in the top 0-1 ft and N rate did not significantly increase grain yield. Although average grain yield was

71% greater across N rates in 2020 compared to 2019 indicating a potentially greater seed N requirement and therefore increasing the likelihood of a grain yield response to N application, data suggest timely precipitation and N supply from N fixation and soil derived N (i.e., 18 lb residual NO_3-N/acre in the 0-1 ft depth and mineralized N) were adequate to satisfy plant and seed N demand. Similar findings were reported by Eckert et al. (2011) and Moraghan et al. (1991), who both observed that N application did not increase grain yield above a soil NO_3-N content of 50 and 14 lb NO_3-N/acre, respectively. Due to a shorter-growing season (i.e., 85 to 100 d), variable June planting conditions, and the unpredictable nature of biological processes associated with N supply and demand, there is some justification for N application in dry bean to ensure yield potentials. Growers may also wish to consider fertilizer placement options as another method to account for some early- to mid-season weather variability, increase nutrient efficiencies, and improve the overall sustainability of the dry bean cropping system.

Post-harvest soil residual NO_3-N was significantly influenced by N rate but not dry bean variety across both years. Residual NO_3-N remaining in the soil following harvest was similar at N rates between 0-60 and 0-90 lb N/acre in 2019 and 2020, respectively (Table 3.04). Nitrogen application rates > 120 lb N/acre maximized post-harvest soil residual NO_3-N indicating application rates were in excess of crop removal. Findings suggest N application greater than grain requirements may potentially increase the risk for environmental N losses due to the ensuing 7–8-month period with little or no plant growth or ground cover prior to spring planting and may also affect the need for starter fertilizer application to the subsequent cash crop.

Dry Bean Response to Sulfur Rate and Source

Grain yield was significantly influenced by variety in 2020 but not affected by S rate or S source across years (Table 3.06, 3.07). Soil S testing may not be a reliable indicator for grain yield response, and large variations in S concentrations can occur between soil horizons (Warncke et al., 2009; Culman et al., 2020). Soil SO_4-S occurrence may be environmentally dependent and site specific, thus soil texture (i.e., SOM) and tissue S concentration may provide a better indication for predicting S availability (Hitsuda et al., 2008; Kaiser and Kim, 2013; Culman et al., 2020). Michigan nutrient management guidelines suggest the critical S concentration within the uppermost trifoliate at R1 is between 0.2%-0.4% S (Vitosh et al., 1995). No S application across both years resulted in tissue S concentrations of 0.25% (Table 3.08) indicating an unlikely response to S application. Field sites consisted of a loam soil with SOM between 2.4 and 2.6% (Table 3.01) suggesting sufficient S may have been available for dry bean growth. Under low soil S conditions nodulation may decrease because S is a key constituent of the nitrogenase enzyme S (Hago and Salama, 1987). However, nodulation was not impacted by S rate which agrees with adequate soil S levels as shown by tissue S concentrations, SOM levels, and lack of grain yield differences. Notably warm soil temperatures at planting (64-68ºF) and S application in more S responsive crops (i.e., corn and wheat) rotated previous to dry bean may reduce the need for supplemental S fertilization. While MESZ is a co-granulated fertilizer containing a mixture of both SO_4-S and elemental S, thus providing some degree of early- and late-season S availability, elemental sulfur must oxidize to SO_4-S by soil microbes prior to becoming plant available (Norton et al., 2013). To allow time for oxidation to take place prior to crop uptake elemental S may require application several months before the growing season (Havlin et al., 2014; Culman et al., 2020). Previous research has found available S from the application of an elemental S and SO_4-S mixture may largely come from the SO_4-S component for the first crop or in the subsequent years after S application (Chien et al., 2016; Degryse et al., 2021). In the current study, all S sources were applied prior to planting. Dry bean is a short-season crop (i.e., 85 to 100 d maturity) creating potential difficulties in allowing for the elemental S component within MESZ to oxidize in time for crop uptake. Gypsum is a common mineral mined from surface and underground deposits and is a readily available and cost-effective source of S within Michigan compared to AS and MESZ fertilizers. However, both AS and MESZ fertilizers contain N in addition to S and are therefore beneficial where both N and S are required. Although gypsum is also a source of calcium (Ca), most soils in Michigan contain sufficient Ca for field crop production and in the current study exchangeable Ca levels (1850-2300 ppm) in 2019 and 2020 suggest no response to Ca was expected (Warncke et al., 2009; Cullman et al., 2020). Compared to MESZ, gypsum increased economic return 20% in 2020 indicating the low cost of gypsum offset lack of yield of differences observed between S sources (Table 3.07). Previous research in dry bean has found nodulation is largely determined by the ratio between N supply and N demand (George and Singleton, 1992; Salvagiotti et al., 2008; Aker et al., 2008; Argraw and Akuma 2015). In 2020 gypsum reduced nodulation up to 2.2 nodules plant^{-1} compared to AS and MESZ (Table 3.08). However, all S sources were balanced to receive 60 lb N/acre indicating it is unlikely N supply influenced nodulation. Additionally, relatively small differences between nodule number per plant among S sources suggest results may not be biologically significant.

Implications for Dry Bean Growers

Two black bean, one small red bean, and one navy bean variety responded similarly to N rate, S rate, and S source, implying the application of N and S may not require adjustments based on specific varieties. While a lack of grain yield response to N application suggests N supply from biological nitrogen fixation and soil-derived N (i.e., residual soil NO_3-N and mineralized

N) were sufficient to satisfy plant N requirements, weather variability can impact early-season N supply and when coupled with a short dry bean growing season (i.e., 85 to 100 d) may support some degree of N fertilizer application to ensure yield potential. Results indicate S application may not be warranted in dry bean grown on fine-textured Michigan soils with > 2% SOM, which agrees with previous reports for this region. Due to the lag time required for elemental S oxidation to SO_4-S, the potential for elemental S to contribute to dry bean S requirements may be limited especially considering the short growing season of this crop and the rotation of dry bean with other potentially S responsive crops (e.g., corn and wheat). Although due to lack of grain yield improvements economic return was not impacted by N or S applications, increased input costs from higher N or S rates may decrease profitability without simultaneous grain yield increases. Incremental increases in N rate increased R5 aboveground dry matter accumulation and R1 trifoliate N concentrations but did not translate into greater grain yield. Rather, increased N rates (i.e., ≥ 60 lb N/acre) generally increased the risk for white mold infection and decreased nodulation in one of two years. Thus, growers should be aware of and consider the risks for excess N applications, which may ultimately reduce grain yield potential and increase environmental loss. Future research verifying dry bean response to N and S application on coarse-textured, irrigated soils in which N and S deficiencies may more commonly occur may be warranted.

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APPENDICES

APPENDIX A:

CHAPTER 3 TABLES

Table 3.01. Soil chemical properties, mean P, K, and S concentrations (0-8 inches), and NO_3-N content (0-1 ft), Richville, MI, 2019-2020.

	Soil test values[a]						
Year	**pH**	**CEC**	**SOM**	**P**	**K**	**S**	**NO_3-N**
		meq/100 g	%	———————	ppm	———————	lb/acre
2019	7.8	15.1	2.6	16	124	6	18
2020	7.0	13.0	2.4	43	162	9	18

[a]Soil test values were obtained prior to fertilizer application.

Table 3.02. Monthly[a] and 30-yr average[b] cumulative precipitation and air temperature for the dry bean-growing season (June-September), Richville, MI, 2019-2020.

Year	**June**	**July**	**August**	**September**	**Total**
			in		
2019	7.0	2.4	1.1	3.8	14.3
2020	1.4	3.2	3.4	2.8	10.8
30-yr avg	3.5	3.1	3.2	3.9	13.7
			˚F		
2019	65.1	72.7	67.9	64.2	269.9
2020	69.1	74.7	70.6	60.4	274.8
30-yr avg	67.5	71.8	69.7	62.2	271.2

[a]Monthly precipitation and air temperatures collected from MSU Enviro-weather (https://enviroweather.msu.edu).
[b]30-yr averages collected from the National Oceanic and Atmosphere Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals)

Table 3.03. Influence of dry bean variety and N rate on tissue N concentration, nodule count, and plant height, Richville, MI, 2019-2020.

	Plant height		Tissue N conc.		Nodule number	
Treatment	**2019**	**2019**	**2019**	**2019**	**2019**	**2020**
	———inches———		———%———		——nodules/plant——	
Variety						
Zenith	20	22 b[a]	4.5	4.6	2.2	7.0 a
Black Bear	20	23 ab	4.5	4.5	2.9	6.9 a
Viper	21	21 c	4.5	4.6	3.2	4.2 ab
Merlin	21	24 a	4.4	4.4	1.0	3.5 b
P > *F*	0.14	0.01	0.93	0.19	0.16	0.02
N rate, lb N/acre						
0	20	22	4.0 e	4.2 d	4.3	7.7 a
30	21	22	4.3 d	4.4 cd	3.2	7.9 a
60	21	22	4.4 cd	4.6 ab	1.9	5.0 ab
90	21	23	4.6 bc	4.5 bc	2.6	3.7 b
120	21	22	4.7 ab	4.6 ab	0.9	4.2 ab
150	21	23	4.8 a	4.7 a	1.0	4.0 b
P > *F*	0.49	0.45	<0.01	<0.01	0.34	0.06

[a]Least square means within each column followed by a common letter are not significantly different at α = 0.10.

Table 3.04. Influence of dry bean variety and N rate on R5 aboveground dry matter accumulation, white mold incidence, and post-harvest residual NO_3-N (0-1 ft), Richville, MI, 2019-2020.

	Aboveground dry matter		**White mold**[a]	**Post-harvest NO_3-N**	
Treatment	**2019**	**2020**	**2020**	**2019**	**2020**
	——lb/acre——		——%——	——lb N/acre——	
Zenith	4545	5445	13 c	27	23
Black Bear	4510	5900	15 c	27	17
Viper	4791	5688	48 a	27	24
Merlin	4667	6326	23 b	29	19
P > *F*	0.89	0.42	<0.01	0.80	0.16
N rate, lb N/acre					
0	3650 c[b]	4355 c	22 b	20 c	17 c
30	4231 bc	5330 bc	20 b	22 bc	15 c
60	4692 ab	6687 a	29 a	24 bc	17 c
90	5229 a	6443 a	21 b	28 b	19 bc
120	4654 ab	6434 a	29 a	37 a	26 ab
150	5314 a	5791 ab	29 a	35 a	32 a
P > *F*	0.01	<0.01	0.02	<0.01	<0.01

[a]No data collected in 2019 due to lack of white mold disease.
[b]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

Table 3.05. Influence of dry bean variety and N rate on grain yield and economic return, Richville, MI, 2019-2020.

Treatment	**Grain yield[a]**		**Economic return[b]**	
	2019	**2020**	**2019**	**2020**
	lb/acre		US$/acre	
Variety				
Zenith	2239	3531 c[c]	634	1021 c
Black Bear	2331	3850 b	661	1117 b
Viper	2262	4223 a	686	1314 a
Merlin	2222	3724 bc	673	1153 b
P > *F*	0.93	0.01	0.80	<0.01
N rate, lb N/acre				
0	2324	3637	721	1128
30	2110	3781	632	1156
60	2199	3915	649	1184
90	2335	3807	681	1136
120	2277	3883	647	1146
150	2337	3968	650	1157
P > *F*	0.87	0.35	0.86	0.87

[a]Grain yield adjusted to 18% moisture.

[b]Economic return calculated as ((dry bean grain price x grain yield) – partial budget costs)).

[c]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

Table 3.06. Impact of dry bean variety and S rate on grain yield and economic return, Richville, MI, 2019-2020.

	Grain yield[a]		**Economic return**[b]	
Treatment	**2019**	**2020**	**2019**	**2020**
	lb/acre		US$/acre	
Variety				
Zenith	2300	3762 b[c]	652	1088 b
Black Bear	2209	4358 a	623	1267 a
Viper	2077	3993 ab	625	1238 a
Merlin	2157	4218 a	650	1310 a
P > F	0.69	0.08	0.93	0.03
S rate, lb S/acre				
0	2172	4040	643	1220
25	2208	4137	648	1246
50	2213	4067	646	1222
100	2150	4088	613	1215
P > F	0.95	0.80	0.80	0.73

[a]Grain yield adjusted to 18% moisture.

[b]Economic return calculated as ((dry bean grain price x grain yield) – partial budget costs)).

[c]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

Table 3.07. Influence of dry bean variety and S source on grain yield and economic return, Richville, MI, 2019-2020.

Treatment	Grain yield[a]		Economic return[b]	
	2019	2020	2019	2020
	lb/acre		US$/acre	
Variety				
Zenith	2142	3935	586	1124
Black Bear	2075	4301	566	1234
Viper	2026	4066	592	1244
Merlin	2060	4000	603	1223
P > *F*	0.94	0.28	0.94	0.21
S source				
Gypsum	2208	4119	648 a[a]	1241
AS[d]	2040	4069	591 ab	1219
MESZ[e]	1979	4037	521 b	1160
P > *F*	0.21	0.81	0.02	0.12

[a]Grain yield adjusted to 18% moisture.

[b]Economic return calculated as ((dry bean grain price x grain yield) – partial budget costs)).

[c]Least square means within each column followed by a common letter are not significantly different at α = 0.10.

[d]AS: ammonium sulfate (21-0-0-24 N-P-K-S).

[e]MESZ: MicroEssentials SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

Table 3.08. Dry bean variety and S rate effects on tissue S concentration and nodule count, Richville, MI, 2019-2020.

Treatment	Tissue S concentration 2019	Tissue S concentration 2020	Nodule number 2019	Nodule number 2020
	———%———		——nodules/plant——	
Variety				
Zenith	0.29 a[a]	0.25	1.2	3.8 a
Black Bear	0.26 b	0.25	3.2	2.5 ab
Viper	0.24 c	0.25	4.0	2.2 b
Merlin	0.25 bc	0.25	0.9	1.3 b
P > F	<0.01	0.18	0.17	0.05
S rate, lb S/acre				
0	0.25 b	0.25	3.0	2.5
25	0.26 a	0.25	1.8	2.0
50	0.26 a	0.25	2.4	2.3
100	0.27 a	0.25	2.1	3.0
P > F	0.03	0.14	0.34	0.37

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

Table 3.09. Dry bean variety and S source effects on tissue S concentration and nodule count, Richville, MI, 2019-2020.

Treatment	Tissue S concentration 2019	Tissue S concentration 2020	Nodule number 2019	Nodule number 2020
	—%—		—nodules/plant—	
Variety				
Zenith	0.28 a[a]	0.26	1.5 bc	4.8 a
Black Bear	0.27 b	0.25	2.6 ab	3.2 b
Viper	0.25 c	0.25	3.6 a	2.3 bc
Merlin	0.26 bc	0.25	0.9 c	1.1 c
P > *F*	0.01	0.19	0.04	0.01
S source				
Gypsum	0.26	0.25	0.9 b	2.0
AS[b]	0.27	0.25	2.5 a	3.4
MESZ[c]	0.26	0.25	3.1 a	3.2
P > *F*	0.17	0.98	<0.01	0.13

[a]Least square means within each column followed by a common letter are not significantly different at α = 0.10.
[b]AS: ammonium sulfate (21-0-0-24 N-P-K-S).
[c]MESZ: MicroEssentials SZ (Mosaic Co.) (12-40-0-10-1 N-P-K-S-Zn).

APPENDIX B:

CHAPTER 3 DATA COLLECTED BUT NOT INCLUDED IN PUBLICATION

Table 3.10. Dry bean variety and N rate effects on V2 and R8 plant stand, Richville, MI, 2019-2020.

	2019		**2020**	
Treatment	**V2**	**R8**	**V2**	**R8**
	———plants/acre———			
Variety				
Zenith	117502 b[a]	106051 c	133269 a	126962 b
Black Bear	110200 c	108208 c	123809 a	122813 b
Viper	133933 a	130115 a	134255 a	139907 a
Merlin	121817 b	123892 b	111196 b	109868 c
P > *F*	<0.01	<0.01	0.01	<0.01
N rate, lb N/acre				
0	120241	116382	126713	119245 c
30	122232	118871	125966	125220 bc
60	122481	114764	130696	122979 bc
90	121983	116258	126713	132190 a
120	116755	116258	123477	126215 ab
150	121485	119867	120241	123477 bc
P > *F*	0.79	0.83	0.16	0.05

[a]Least square means within each column followed by a common letter are not significantly different at $\alpha = 0.10$.

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