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Soybean seeding rate and fertilizer effects on growth, partitioning, and yield

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Abstract

Greater soybean (*Glycine max* L. Merr.) total dry matter (TDM) production may support yield potential and correspondingly drive greater nutrient uptake. Whether increased dry matter (DM) and reduced interplant competition at decreased seeding rates improves grain yield response to fertilizer applications is not clear. A 3-site-year trial was conducted to evaluate soybean seeding rates and fertilizer applications on plant growth, nutrient accumulation, grain yield, and economic return. Seeding rates included: 123,500; 222,400; 321,200; and 420,100 seeds ha^{-1}. Fertilizer applications consisted of: unfertilized; 90 kg MOP (0−0−62 N−P−K) ha^{-1} pre-plant incorporated (PPI); 168 kg MESZ (12-40−0−10−1 N−P−K−S−Zn) ha^{-1} applied 5 by 5 cm below and to the side of the seed at planting (5 × 5); and 90 kg MOP ha^{-1} PPI and 168 kg MESZ ha^{-1} applied 5 × 5. Dry matter (V4) increased 37.7 to 116.6% and 73.3 to 137.5% with seeding rates ≥222,400 seeds ha^{-1} and MESZ applications, respectively, with greater early-season DM supporting increased nutrient uptake and grain yield potential. Increasing seeding rate from 123,500 to 222,400 seeds ha^{-1} improved grain yield 9% but no differences were observed above 222,400 seeds ha^{-1}. The MESZ and MOP+MESZ applications increased grain yield 7.4 and 6.9%, respectively, while MOP did not affect grain yield across site-years. As emphasis on creating more durable, resilient agroecosystems continues, results suggest seeding rates ≥222,400 seeds ha^{-1} maximized DM accumulation facilitating nutrient uptake which may be paramount to improving fertilizer management or reducing post-harvest residual soil nutrients in impaired watersheds or regions of greater nutrient loss potential.

1 | INTRODUCTION

Michigan 2018 soybean (*Glycine max* L. Merr.) yield (3228 kg ha^{-1}) coupled with recently stagnant or decreasing soybean commodity prices (i.e., US\$0.20 kg^{-1} decline since 2013) have prompted interest in focusing fertilizer applications (USDA-NASS, 2018a, 2018b). Biological nitrogen fixation (BNF) and soil N may fulfill soybean grain N requirements in grain yields ≤4500 kg ha^{-1} and provide

Abbreviations: 5 × 5, subsurface band placement 5-cm below and laterally; BNF, biological nitrogen fixation; DM, dry matter; HI, harvest index; MESZ, 12−40−0−10−1 N−P−K−S−Zn; MOP, 0−0−62 N−P−K; PPI, pre-plant incorporated; R5DM, R5 dry matter; R8TDM, R8 total dry matter; SOM, soil organic matter; TDM, total dry matter; V4DM, V4 dry matter.

95–97% of maximum yield when soil P, K, and micronutrient supply exceeds critical concentrations (i.e., potential for < 5% grain yield increase to fertilizer applications when soil nutrient concentrations are adequate) (Salvagiotti et al., 2008; Warncke, Dahl, & Jacobs, 2009). Interplant competition may further limit grain yield response to fertilizer application for plant densities between 1.5–6.0 plants m^{-2} (Duncan, 1986; Egli, 1988b; Havlin, Tisdale, Beaton, & Nelson, 2014) creating additional difficulties for developing widely applicable, plant-responsive, fertilizer management strategies. From 1931 to 2017, total dry matter (TDM) increased from 4700 to 10,700 kg ha^{-1} and grain yield increased from 1200 to 5500 kg ha^{-1} (Borst & Thatcher, 1931; Gaspar, Laboski, Naeve, & Conley, 2017a). Increased grain yields and nutrient uptake from 1930 to 2017 may be due to increased TDM (0.025 Mg ha^{-1} yr^{-1}) rather than grain production per unit of TDM (i.e., harvest index [HI]; 0.0008 yr^{-1}) (Balboa, Sadras, & Ciampitti, 2018). Greater TDM in modern soybean varieties and reduced interplant competition from decreased seeding rates (i.e., <300,000 seeds ha^{-1}) may facilitate increased nutrient accumulation and provide opportunities to capitalize on (i.e., increase yield) fertilizer applications (Balboa et al., 2018; Bender, Haegele, & Below, 2015; Board, 2000; Salvagiotti et al., 2008; Warncke et al., 2009).

Positive correlations between TDM and grain yield exist (Ball, Purcell, & Vories, 2000; Gaspar et al., 2017a; Parvez, Gardner, & Boote, 1989). Maximum dry matter (DM) provides potential for increased nutrient uptake, nutrient remobilization, and grain yield potential while simultaneously reducing the risk for nutrient loss (Bender et al., 2015). However due to temporal influence of environmental conditions on vegetative and reproductive growth, TDM has previously been a poor predictor of grain yield (Shibles & Weber, 1966; Weber, Shibles, & Byth, 1966). Greater soybean planting densities (i.e., ≥300,000 seeds ha^{-1}) tend to increase competitiveness with weeds, light interception, and grain yield potential but additional interplant competition for sunlight and other resources (e.g., water and nutrients) may contribute to DM accumulation and grain yield plateaus (Ball et al., 2000; Harder, Sprague, & Renner, 2007; Holliday, 1960; Norsworthy & Oliver, 2001). Chen and Wiatrak (2011) suggested greater early-season DM may be achieved with increased seeding rates but TDM plateaued above 272,000 seeds ha^{-1}. Decreased seeding rates (i.e., <300,000 seeds ha^{-1}) can reduce production costs, plant lodging, and disease severity and result in comparable grain yield (i.e., 95% of maximum yield) through increased crop growth rate, TDM, and branch and pod production (Ball et al., 2000; Carpenter & Board, 1997b; De Bruin & Pedersen, 2008; De Souza Jaccoud-Filho et al., 2016; Egli, 1988a; Lee, Egli, & TeKrony, 2008; Suhre et al., 2014; Wells, 1993). Modern soybean germplasm offers increased compensation ability at reduced planting populations and improved tolerance to interplant competition at increased planting populations which may concomitantly influence DM and therefore nutrient accumulation (De Bruin & Pedersen, 2009; Suhre et al., 2014).

Core Ideas

- V4 dry matter per plant responded greater to MESZ applications at reduced seeding rates (i.e., 123,500 seeds ha^{-1}) but diminished due to accelerating crop growth rates.
- Fertilizer application rates may not need to be adjusted for seeding rates.
- Maximum grain yield was achieved at 364,300 seeds ha^{-1} while net economic return was maximized at 265,300 seeds ha^{-1}.
- Treatments associated with greater yields obtained greater dry matter prior to R5 compared to treatments with no yield increases.
- Reduced seeding rates (i.e., 123,500 seeds ha^{-1}) increased potential for grain loss due to branching closer to the soil surface.

In 2012, 44, 43, and 69% of Michigan soybean hectares were fertilized with N, P, and K, respectively (USDA-NASS, 2012). Potential for a grain yield increase to fertilizer applications may be dependent on site-specific factors (i.e., soil and physical properties and precipitation) (Clover & Mallarino, 2013; Hankinson, Lindsey, & Culman, 2015; Warncke et al., 2009). However, grower interest in N, P, K, S, and Zn applications continues to increase due to volatile spring environmental conditions, variable soil texture, decreased atmospheric S deposition in the north-central United States, perceived increases in micronutrient deficiencies, and to ensure yield potential of modern higher-yielding cultivars (i.e., yield potential >4500 kg ha^{-1}) (Chien et al., 2016; Havlin et al., 2014; Hitsuda, Toriyama, Subbarao, & Ito, 2008; Osborne & Riedell, 2006; Sutradhar, Kaiser, & Behnken, 2017; Tamagno, Sadras, Haegele, Armstrong, & Ciampitti, 2018). Gaspar, Laboski, Naeve, and Conley (2017b) reported grain K requirements relied on vegetative remobilization past R5.5 emphasizing the importance of K tissue concentrations to support soybean DM and K accumulation prior to grainfill. Additionally, subsurface fertilizer applications at planting may increase both early and late season nutrient availability and help mitigate inconsistent grain yield responses to foliar fertilizer applications as grain N, P, S, and Zn requirements rely upon soil uptake after R5.5 rather than vegetative remobilization (Gaspar et al., 2017a, 2017b, 2018; Orlowski et al., 2016). Minimal BNF N contributions until V2−V4 contributing to spatial and temporal soil N inconsistencies coupled with cool, wet springs in Michigan that slow root growth may

TABLE 1 Soil chemical properties, mean nutrient concentrations (0–20-cm depth), and critical values[a], Richville and Lansing, MI, 2017–2018

			Soil test values[b]					
Location	**Year**	**pH**	**CEC**	**SOM**	**P**	**K**	**S**	**Zn**
			cmol kg^{-1}	g kg^{-1}	mg kg^{-1}			
Richville	2017	8.2	16.2	26	23 (15)	155 (116)	7 (na)[c]	6 (7)
Lansing	2017	6.6	7.6	21	30 (15)	134 (94)	8 (na)	2 (2)
	2018	7.1	11.9	28	49 (15)	106 (105)	8 (na)	3 (7)

[a] Soil test values in parenthesis represent critical values for each soil (Warncke et al., 2009).

[b] pH (1:1, soil/water) (Peters, Nathan, & Labowski, 2015); CEC, cation exchange capacity (Warncke, Robertson, & Mokma, 1980); SOM, soil organic matter (loss-on-ignition) (Combs & Nathan, 2015); P (Bray-P1) (Frank, Beegle, & Denning, 2015), K (ammonium acetate method) (Warncke & Brown, 2015), S (monocalcium phosphate extraction) (Combs, Denning, & Frank, 2015), Zn (0.1 M HCl extraction) (Whitney, 2015).

[c] na, not available. Soil S testing can be unreliable and a poor indicator of S availability (Hitsuda et al., 2008; Chien et al., 2016).

further provide opportunities to influence early-season DM and nutrient accumulation with starter fertilizer application (Havlin et al., 2014; Osborne & Riedell, 2006; Tamagno et al., 2018; Warncke et al., 2009). Limited data exist examining opportunities to maximize DM and grain yield in response to combinations of seeding rates and fertilizer applications.

Dry matter partitioning previously was thought to be distributed into leaves, stems, pods, and grain at 25, 27, 19, and 29%, respectively (Borst & Thatcher, 1931). However in modern soybean varieties, Bender et al. (2015) reported 16, 33, 14, and 37% of TDM partitioning into leaves, stems, pods, and grain, respectively, and greater stem distribution in current cultivars may support greater yield on lateral branches as compared to the main stem (Hanway & Weber, 1971; Suhre et al., 2014). Egli, Guffy, and Leggett (1985) reported soybean-partitioning ratios were not affected by seeding rates. However, Wilcox (1974) and Spaeth, Randall, Sinclair, and Vendeland (1984) suggested increased grain removal relative to TDM (i.e., HI) at decreased seeding rates. Additionally, Gaspar et al. (2017a) suggested HI may vary by yield level. Seeding rate and fertilizer application affecting grain yield and DM distribution may in tandem influence nutrient uptake, partitioning, and removal (Bender et al., 2015; Gaspar et al., 2017a). The objective of this study was to evaluate the effects of seeding rate and fertilizer application on DM accumulation and partitioning, nutrient uptake, grain yield, and net economic return.

2 | MATERIALS AND METHODS

Field trials were conducted in 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 Epiaquolls) in 2017 and in Lansing, MI (42°42′37.0″N, 84°28′14.6″W) on a non-irrigated Capac loam soil (fine-loamy, mixed, active, mesic Aquic Glossudalf) in 2017 and 2018. All sites were previously cropped to corn (*Zea mays* L.) with autumn chisel plow (20-cm depth) and spring field cultivation (10-cm depth). Pre-plant soil samples (20-cm depth) were collected prior to fertilizer application, ground to pass through a 2-mm sieve, and analyzed for soil chemical properties (Table 1). Weed control consisted of an application of S-metolachlor {2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acetamide} and glyphosate [N-(phosphonomethyl) glycine] followed by a second application of glyphosate across site-years. In Lansing 2017, lambda-cyhalothrin {[1a(S*),3a(Z)]-cyano(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2- dimethylcyclopropanecarboxylate)} was applied on 19 July for Japanese beetle (*Popillia japonica*) leaf feeding damage. 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-yr means were obtained from the National Oceanic and Atmosphere Administration (NOAA, 2018).

Trials were arranged as a randomized complete-block split-plot design with four replications. Main plots consisted of seeding rate while subplots were fertilizer application. The four seeding rates were 123,500; 222,400; 321,200; and 420,100 seeds ha^{-1}. The targeted seeding rate of 123,500 seeds ha^{-1} resulted in a seeding rate of 135,900 seeds ha^{-1} therefore plots were thinned to 123,500 seeds ha^{-1} at V1 while all other plant populations were within 10% of the targeted seeding rate as evidenced by stand counts (Fehr & Caviness, 1977; Hicks, Lueschen, & Ford, 1990). Four fertilizer treatments included: (a) an unfertilized control, (b) 90 kg MOP ha^{-1} PPI, (c) 168 kg MicroEssentials SZ (MESZ) (Mosaic Co.) ha^{-1} applied 5 by 5 cm below and to the side of the seed at planting (5 × 5), and (d) a combination of MOP PPI and MESZ 5 × 5 (MOP+MESZ). Plots measured 12.2 m in length and 4.6 m in width and were planted with a Monosem planter (Monosem Inc.) in 76-cm rows using the variety AG2535 (Monsanto Co.). Planting dates were 27 Apr. 2017 in Richville and 10 May 2017 and 9 May 2018 in Lansing.

Aboveground biomass samples were collected at V4, R2, R5, and R8 growth stages when approximately 50% of plants

TABLE 2 Monthly[a] and 30-yr mean[b] temperature and precipitation data for the soybean growing season, Richville and Lansing, MI, 2017–2018

Location	Year	Apr.	May	June	July	Aug.	Sept.	Total	July–Sept.
					cm				
Richville	2017	14.7	5.0	12.3	2.8	5.7	4.0	44.5	Deficit[c]
	30 yr	7.3	8.6	7.6	6.6	8.4	9.7	48.2	–
Lansing	2017	13.3	6.6	8.4	6.7	3.5	3.3	41.8	Deficit
	2018	6.0	12.6	3.7	2.7	11.7	10.3	47.0	Normal
	30 yr	7.7	8.5	8.8	7.2	8.2	8.9	49.3	–
					°C				
Richville	2017	10.3	13.7	20.4	21.2	19.3	17.9	–	–
	30 yr	7.8	14.1	19.6	21.7	20.4	16.3	–	–
Lansing	2017	11.1	13.7	19.9	21.7	19.3	17.9	–	–
	2018	4.1	17.6	20.0	21.9	21.8	18.0	–	–
	30 yr	8.6	14.3	19.8	21.9	21.0	16.6	–	–

[a] Monthly precipitation and air temperatures collected from MSU Enviro-weather (https://enviroweather.msu.edu).

[b] Thirty-year means collected from the National Oceanic and Atmosphere Administration (https://www.ncdc.noaa.gov/cdo-web/datatools/normals).

[c] Cumulative precipitation July–September considered normal if within 10% of 30-yr mean, deficit if $\geq$10% below 30-yr mean, and excessive if $\geq$10% above 30-yr mean.

reached the respective growth stage (Fehr & Caviness, 1977). Dry matter sampling areas were selected from the second row within each plot and consisted of 10 consecutive aboveground portion of plants that were partitioned into leaves, stems and petioles, flowers and pods, and grain (Bender et al., 2015). Prior to the onset of leaf senescence, 1- by 1-cm netting was assembled around sampling areas to retain senesced DM. To determine dry weight, plant tissues were dried at 66 °C (0% moisture) and total DM accumulation reported as the dry weight sum of all plant components. Aboveground-plant V4 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. A research plot combine (Almcao) harvested the center two rows for grain yield, moisture, and test weight with yield adjusted to 135 g kg^{-1} moisture. Net economic return was calculated using a partial budget by subtracting input cost from gross revenue (i.e., grain price multiplied by yield). Input costs included seed, fertilizer, and application costs obtained from local grain elevators and retailers. Soybean grain prices were \$351.27 Mg^{-1} in 2017 and \$318.57 Mg^{-1} in 2018. Fertilizer costs were \$0.33 and \$0.54 kg^{-1} and \$0.39 and \$0.65 kg^{-1} for MOP and MESZ during 2017 and 2018, respectively. Seed cost estimates for 2017 and 2018 were \$82.50 140,000 seeds^{-1}. Application costs were estimated from the Michigan State University Extension Custom Machine and Work Rate Estimates and included \$4.65, \$16.16, and \$33.63 ha^{-1} for subsurface 5 × 5 nutrient application, MOP broadcast application, and MOP incorporation, respectively (Stein, 2016).

Data were analyzed in SAS 9.4 (SAS Institute, 2012) using the GLIMMIX procedure. Site-year, seeding rate, and fertilizer application were considered fixed effects and 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 ($P \leq .10$). A quadratic plateau model was developed to investigate the response of grain yield and economic return to seeding rate using the NLIN procedure. Pearson product-moment correlations were derived using the REG procedure of SAS to investigate the relationship between DM accumulation and net economic return with grain yield and final DM accumulation with R8 grain nutrient accumulation.

3 | RESULTS AND DISCUSSION

3.1 | Environmental conditions

Total 2017 growing season (April−September) precipitation was 8 and 15% below the 30-yr mean in Richville and Lansing, respectively, but 49 and 44% below the 30-yr mean at these locations during the critical July through September pod development and grain-fill periods (Table 2). In 2018, total growing season precipitation and July through September rainfall volumes in Lansing were within 5 and 2% of the 30-yr mean, respectively. Dry soil conditions from deficit precipitation (i.e., greater than 10% below the 30-yr mean) during July–September 2017 at both locations and July 2018

TABLE 3 Interaction between soybean seeding rate and fertilizer application ($P < .01$) on V4 individual aboveground-plant dry matter (DM) production, across locations and years, Richville and Lansing, MI, 2017 to 2018. All values reported on a dry weight (0% moisture) basis

Fertilizer	Seeding rate, seeds ha^{-1} 123,500	222,400	321,200	420,100	$P > F$
	g plant^{-1}				
Non-fertilized	1.12 b[a]A[b]	0.95bB	0.79bC	0.71bC	<.01
MOP[c]	1.18bA	0.89bB	0.82bB	0.70bC	<.01
MESZ[d]	2.43aA	1.83aB	1.55aC	1.21aD	<.01
MOP + MESZ	2.50aA	1.85aB	1.47aC	1.28aC	<.01
$P > F$	<.01	<.01	<.01	<.01	–
Response to MESZ[e]	1.34A	0.85B	0.72B	0.54C	<.01

[a] Values followed by the same lowercase letter within each column are not significantly different at $\alpha = .10$.

[b] Values followed by the same uppercase within each row are not significantly different at $\alpha = .10$.

[c] MOP: muriate of potash (0–0–62 N–P–K).

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

[e] Response to MESZ multiple degree of freedom contrasts was the mean plant dry materials from treatments receiving MESZ application minus plant dry matter from treatments receiving no nutrient application within each respective seeding rate.

may have limited nutrient movement and grain yield potential across site-years. Mean May 2017 air temperatures were within 0.4 and 0.6 °C of the 30-yr mean in Richville and Lansing, respectively, and 3.3 °C above the 30-yr mean for Lansing May 2018. June through September mean monthly air temperatures were within 1.6 °C of the 30-yr mean across site-years.

3.2 | Dry matter production and nutrient accumulation

An interaction between seeding rate and fertilizer treatment ($P < .01$) influenced soybean V4 DM production per plant (g plant^{-1}). Site-year and its interactions did not influence V4 DM therefore treatment interaction means were presented across locations and years (Table 3). Maximum V4 DM production per plant occurred at 123,500 seeds ha^{-1} (1.12–2.50 g plant^{-1}) and progressively decreased at each sequentially greater seeding rate interval. Reductions of 0.17–0.67 g plant^{-1} and 0.16–0.38 g plant^{-1} in individual plant DM when going from the 123,500–222,400 seeds ha^{-1} and the 222,400 and 321,200 seeds ha^{-1} seeding rates, respectively, indicated interplant competition prior to the V4 growth stage (Carpenter & Board, 1997a). Although reduced planting densities (e.g., 70,000 plants ha^{-1}) may experience decreased overall growth rates (g m^{-2} d^{-1}) for up to 30 d after emergence compared to greater plant populations (e.g., 164,000–234,000 plant ha^{-1}) and may not produce similar growth rates until R1, increased leaf area in response to decreased seeding rate is considered important for aboveground soybean plasticity and required to support greater branch and pod production (Carpenter & Board, 1997a, 1997b; Board, 2000). Current trial results, however, agree with Board (2000) who found 80,000 plants ha^{-1} increased plant growth rate 21 d after soybean emergence compared to 145,000–390,000 plants ha^{-1}. Results suggest interplant competition from greater seeding rates (i.e., ≥222,400 seeds ha^{-1}) may limit early-season plant growth. Across fertilizer treatments, MESZ application produced more DM plant^{-1} (0.57–1.38 g plant^{-1}), and in several instances the additional DM produced was sufficient to offset reductions in DM due to greater seeding rates. When the mean of treatments not receiving MESZ was subtracted from the mean of treatments with MESZ application (i.e., response to MESZ), individual plant DM increased 76 to 120% (0.54–1.34 g plant^{-1}) across all seeding rates. Results indicate that reduced population densities increased the per plant DM response to MESZ application. Growers should be aware however that accelerated V4–R1 crop growth rates may reduce vegetative responses observed prior to V4 and often may not translate into grain yield increases (Bender et al., 2015; Gaspar et al., 2017a).

An interaction between site-year and seeding rate ($P < .01$) affected total V4 aboveground DM accumulation (V4DM) (kg ha^{-1}) (Table 4). Within each site-year, increasing seeding rate from 123,500 to ≥222,400 seeds ha^{-1} increased V4DM indicating interplant competition did not limit V4DM. In 2017, V4DM did not increase above 321,200 and 222,400 seeds ha^{-1} in Richville and Lansing, respectively. Alessi and Power (1982) suggested increased seeding rates limited crop growth under moisture-limiting conditions by depleting early-season water reserves. In 2017, both locations received deficit May precipitation (42 and 22% below the 30-yr mean in Richville and Lansing, respectively) which likely limited V4DM accumulation at greater seeding rates. Total 2017 precipitation between planting to V4 was 8.9 and 5.3 cm in Richville and Lansing, respectively, and V4DM may have been limited at lower seeding rates in Lansing (i.e., 222,400 seeds ha^{-1}) compared to Richville (i.e., 321,200 seeds ha^{-1}) due to less precipitation. In contrast to

TABLE 4 Soybean seeding rate and fertilizer application effects on V4 aboveground dry matter accumulation across years, Richville and Lansing, MI, 2017 to 2018. All values reported on a dry weight (0% moisture) basis

Treatment	Location Richville, 2017	 Lansing, 2017	 Lansing, 2018
		kg ha^{-1}	
Seeding rate, seeds ha^{-1}			
123,500	276b^{a}	166b	211d
222,400	311b	284a	325c
321,200	399a	313a	394b
420,100	380a	311a	457a
$P > F$	<.01	<.01	<.01
Fertilizer			
Non-fertilized	237b	160b	249b
MOP^{b}	251b	160b	243b
MESZ^{c}	443a	373a	441a
MOP + MESZ	435a	380a	454a
$P > F$	<0.01	<0.01	<0.01

[a] Values followed by the same letter are not significantly different at $\alpha = .10$.

[b] MOP: muriate of potash (0–0–62 N–P–K).

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

2017, V4DM in 2018 was maximized at 420,100 seeds ha^{-1} in Lansing. Extensive May 2018 precipitation (i.e., 48% above the 30-yr mean) and 13.4-cm precipitation occurring between planting and V4 at this location suggested early-season plant growth was not limited at greater plant populations. Current data suggest increased seeding rates limited soybean growth during dry environmental conditions (i.e., Richville and Lansing 2017) but supported additional growth and interplant competition when soil moisture was not limiting (i.e., 2018).

Site-year and fertilizer influenced V4DM (kg ha^{-1}) ($P < .01$) (Table 4). At no point did MOP applications influence V4DM indicating that plant K requirements prior to V4 were sufficiently supplied by the soil (Warncke et al., 2009). Relative to the unfertilized treatment, subsurface MESZ application increased mean V4DM 85, 135, and 79% in Richville and Lansing 2017 and Lansing 2018, respectively. The MESZ fertilizer is a co-granulated product containing N, P, S, and Zn. Soybean BNF may not occur until V2–V4 suggesting V4 plant N requirements may rely on residual soil N and soil organic matter (SOM) mineralization (Tamagno et al., 2018). Soil organic matter concentrations (21–28 g kg^{-1}) and cool soil temperatures at planting (13.1–18.8 °C) indicated some potential for increased early-season (i.e., V4) DM in response to N in the MESZ application (Taylor, Weaver, Wood, & van Santen, 2005; Cigelske, 2016). Sufficient soil P concentrations (23–49 mg kg^{-1}) and lack of visual tissue deficiency symptoms suggest P contributions to increased V4DM were unlikely (Warncke et al., 2009). Minimal S accumulation prior to V4 (< 10%) coupled with lack of previous increased DM response to S application until R2 suggest the S component in MESZ also may not have influenced V4DM (Boem, Prystupa, & Ferraris, 2007; Gaspar, Laboski, Naeve, & Conley, 2018). However, soil Zn concentrations (2–6 mg kg^{-1}) and soil pH (6.6–8.2) across locations indicated the potential for Zn deficiency (Zn recommendation = {[(5.0 x pH) − (0.4 x soil nutrient concentration)] − 32} but no visual Zn deficiencies were observed (Warncke et al., 2009). Benefits to increased plant size may include greater photosynthetic capacity and a larger root system able to support or initiate BNF and soil nutrient uptake earlier, but yield-limiting factors including plant lodging and disease severity (e.g., white mold [*Sclerotinia sclerotiorum*]) must be accounted for (Ball et al., 2000; Salvagiotti et al., 2008; De Souza Jaccoud-Filho et al., 2016; Tamagno et al., 2018). Subsurface banded fertilizer applications have previously been observed to increase early-season DM and nutrient accumulation in corn (*Zea mays* L.) (Niehues, Lamond, Godsey, & Olsen, 2004; Rutan & Steinke, 2018). As soybean growers respond to a changing climate and plant earlier in the season due to warmer air and soil temperatures, similar benefits may exist in soybean production (Hankinson et al., 2015).

Due to similar nutrient accumulation patterns in leaves and stems (data not shown), early-season (V4) aboveground-plant nutrient accumulation data (kg ha^{-1}) were presented as the interaction between site-year and treatment (Table 5). Greater nutrient accumulation generally occurred with increased seeding rates (i.e., $\geq$222,400 seeds ha^{-1}) and MESZ applications. Correlation analysis indicated a positive relationship between V4DM and N, P, K, S, and Zn nutrient uptake (kg ha^{-1}) ($r = .90–.99$; $P < .01$) suggesting increased DM production may have enabled greater nutrient uptake (Bender et al., 2015). Greater TDM in current soybean varieties emphasizes the importance for maintaining above critical soil nutrient concentrations to support early-season DM and nutrient accumulation.

Previous research reported limited early-season nutrient accumulation until approximately R1 (Bender et al., 2015). Gaspar et al. (2017a, 2017b, 2018) found higher grain yields (i.e., 5500 kg ha^{-1}) decreased the time interval for nutrient accumulation and termed this the “lag-phase”. Increased DM through increased seeding rates (i.e., $\geq$ 222,400 seeds ha^{-1}) and subsurface MESZ applications likely reduced the “lag-phase” of soybean nutrient uptake. Previous research indicated DM and nutrient uptake at V4 were less than 20% of total accumulation and that the majority of grain nutrient requirements were supplied from the soil during grain-fill rather than vegetative nutrient remobilization (Bender et al., 2015; Gaspar et al., 2017a, 2018). However, when soil nutrient availability is insufficient to meet plant demands, vegetative nutrient remobilization may fulfill grain nutrient

TABLE 5 Soybean seeding rate and fertilizer application effects on V4 total nutrient accumulation, Richville and Lansing, MI, 2017 and 2018

		Aboveground plant nutrient accumulation[a]				
Site-year	**Main effect**	**N**	**P**	**K**	**S**	**Zn**
		kg ha^{-1}				g ha^{-1}
Richville, 2017	Seeding rate, seeds ha^{-1}					
	123,500	11b[b]	1.1b	8c	0.7b	12b
	222,400	11b	1.2b	9bc	0.8b	13b
	321,200	14a	1.5a	11ab	0.9a	16a
	420,100	13a	1.4a	10a	0.9a	15a
	$P > F$	<.01	< .01	<.01	<.01	<.01
	Nutrient application					
	Non-fertilized	9b	0.9b	7b	0.6b	11b
	MOP[c]	9b	0.9b	7b	0.6b	12b
	MESZ[d]	16a	1.6a	11a	1.1a	17a
	MOP + MESZ	16a	1.6a	11a	1.0a	17a
	$P > F$	<.01	< .01	<.01	<.01	<.01
Lansing, 2017	Seeding rate, seeds ha^{-1}					
	123,500	7b	0.7b	5b	0.5b	9b
	222,400	12a	1.1a	8a	0.8a	15a
	321,200	12a	1.2a	8a	0.8a	15a
	420,100	12a	1.1a	8a	0.8a	14a
	$P > F$	<.01	< .01	<.01	<.01	<.01
	Nutrient application					
	Non-fertilized	6b	0.6b	5b	0.4b	7b
	MOP	7b	0.6b	5b	0.4b	8b
	MESZ	15a	1.5a	10a	1.0a	20a
	MOP + MESZ	15a	1.5a	10a	1.0a	19a
	$P > F$	<.01	< .01	<.01	<.01	<.01
Lansing, 2018	Seeding rate, seeds ha^{-1}					
	123,500	8c	0.9d	4c	0.6d	8c
	222,400	12b	1.4c	6b	0.9c	14b
	321,200	14a	1.7b	7b	1.1b	15b
	420,100	15a	1.9a	9a	1.3a	19a
	$P > F$	<.01	<.01	<.01	<.01	<.01
	Nutrient application					
	Non-fertilized	9b	1.0b	5b	0.7b	10b
	MOP	9b	1.0b	5b	0.7b	10b
	MESZ	15a	1.9a	8a	1.3a	19a
	MOP + MESZ	15a	1.9a	8a	1.3a	18a
	$P > F$	<.01	<.01	<.01	<.01	<.01

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

[b] Values followed by the same letter are not significantly different at $\alpha = .10$.

[c] MOP: muriate of potash (0–0–62 N–P–K).

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

requirements but reduces the photosynthetic capacity and grain yield potential (Salvagiotti et al., 2008, 2009).

Total R5 and R8 dry matter accumulation (R5DM and R8TDM, respectively) ranged between 5000–6126 kg ha^{-1} and 8229–9192 kg ha^{-1}, respectively (data not shown), but were not affected by seeding rate, fertilizer treatment, or any interaction likely due to accelerated post-R1 crop growth rates which peaked by R4 (Bender et al., 2015). Implementation of soybean seeding rate or fertilizer application programs solely to enhance DM production may be

TABLE 6 Soybean grain nutrient accumulation at physiological maturity (R8) as affected by seeding rate and fertilizer application presented across locations and years, Richville and Lansing, MI, 2017–2018

	Grain nutrient accumulation[a]				
Treatment	**N**	**P**	**K**	**S**	**Zn**
	kg ha^{-1}				g ha^{-1}
Seeding rate, seeds ha^{-1}					
123,500	243a[b]	22a	83a	13a	167a
222,400	225a	20a	75a	12a	150a
321,200	216a	19a	72a	11a	144a
420,100	229a	20a	77a	12a	154a
$P > F$	.28	.13	.16	.12	.12
Fertilizer					
Non-fertilized	229a	20a	76a	12bc	153a
MOP[c]	216a	20a	74a	11 c	148a
MESZ[d]	237a	21a	79a	13a	159a
MOP + MESZ	230a	21a	77a	13ab	156a
$P > F$	.27	.27	.56	<.01	.46

[a] Grain nutrient accumulation calculated as nutrient concentration × grain dry matter accumulation.

[b] Values followed by the same letter are not significantly different at α = .10.

[c] MOP: muriate of potash (0–0–62 N–P–K).

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

more successful on marginally productive soils or in those areas where yield-limiting factors may already be known to exist (e.g., deficient soil nutrient concentrations, sudden death syndrome [*Fusarium virguliforme*], or soybean cyst nematode [*Heterodera glycines*]).

Grain nutrient accumulation data (kg ha^{-1}) at maturity (R8) were presented across locations and years due to no effect of site-year or its interactions. At grain yields of 3400–3800 kg ha^{-1}, grain nutrient accumulation ranged from 216 to 243 kg N ha^{-1}, 19 to 22 kg P ha^{-1}, 72 to 83 kg K ha^{-1}, 11 to 13 kg S ha^{-1}, and 144 to 167 g Zn kg^{-1} (Table 6). Similar DM and HI among seeding rates and adequate soil nutrient concentrations indicated no differences in grain nutrient accumulation should be expected. Macronutrient removal in grain was previously reported to remain unaffected by soybean grain yield potential or variety when soil nutrient concentrations were sufficient (Gaspar et al., 2017a,b). Grain nutrient concentrations within seeding rate and fertilizer treatment ranged from 59 to 60 g N kg^{-1}, 5.09 to 5.34 g P kg^{-1}, 19.8 to 20.1 g K kg^{-1}, 3.03 to 3.29 g S kg^{-1}, and 39.8 to 40.8 mg Zn kg^{-1} (data not shown) and were in agreement with current removal values (Warncke et al., 2009; Bender et al., 2015). However, increased DM in current soybean varieties simultaneously increased nutrient accumulation and grain yield and therefore total nutrient requirements (Bender et al., 2015). Lack of differences in grain nutrient accumulation across seeding rates suggest producers utilizing either above or below recommended seeding rates should follow university fertilizer recommendation guidelines to maintain soil nutrient concentrations.

Across fertilizer treatments, R8 grain S accumulation (kg ha^{-1}) was the only nutrient affected and increased from 12 to 13 kg ha^{-1} with MESZ application (Table 6). Due to the lack of reliability with soil S testing, Hitsuda, Sfredo, and Klepker (2004) previously quantified seed concentrations below 2.3 g S kg^{-1} as deficient. Grain S concentrations in the current study (3.03–3.29 g kg^{-1}) suggest adequate S supply regardless of seeding rate and fertilizer treatment. Delayed S availability with elemental S, grain S requirements that rely on continuous soil uptake past grain-fill, direct partitioning of nutrients accumulated past R5.5 to grain, and a large S HI (70%) may have increased grain S accumulation with MESZ applications (Chien et al., 2016; Gaspar et al., 2018). However, grain S accumulation may also be dependent on early-season nutrient uptake and remobilization efficiency from vegetative and other reproductive tissues (Sunarpi & Anderson, 1997; Naeve & Shibles, 2005). Nutrient remobilization dynamics continue to emphasize the importance of maintaining sufficient soil nutrient concentrations. Soybean grown on low organic matter soils (i.e., < 20 g kg^{-1}) and non-manured sites with no immediate history of previous S application may better benefit from soil applied S.

3.3 | Dry matter partitioning

Physiological maturity (R8) TDM partitioning data were combined across locations and years due to few differences between treatments or ranges for individual plant components (Table 7). Total DM partitioned into leaves, stems and petioles, flowers and pods, and grain consisted of 12–14, 26–29, 14–17, and 44–45%, respectively, closely resembling the results from Bender et al. (2015). Total DM partitioning was reported to remain similar across fertilizer treatments (Bender et al., 2015) and seeding rates (Egli et al., 1985). However in high yield environments (i.e., 5500 kg ha^{-1}), Gaspar et al. (2017a) reported greater TDM and grain HI which can affect stem and leaf allocation. Compared to pre-2000 released soybean cultivars, current soybean germplasm increased TDM and stem DM partitioning to support increased grain yield on plant branches (Hanway & Weber, 1971; Suhre et al., 2014). Although DM allocation may vary with factors affecting plant growth and development (i.e., environmental conditions, soil nutrient availability, and precipitation frequency) (Egli, Meckel, Phillips, Radcliffe, & Leggett, 1983; Chen & Wiatrak, 2010), minimal TDM partitioning differences suggest soybean DM management should focus on other management factors (e.g., pest and disease control, moisture availability) rather than seeding rate or fertilizer application when soil nutrient concentrations are above critical concentrations.

TABLE 7 Influence of soybean seeding rate and fertilizer application on R8 total dry matter partitioning presented across locations and years, Richville and Lansing, MI, 2017–2018

	Leaves		**Stems/Petioles**		**Flowers/Pods**		**Grain**	
Treatment	**Avg.**	**Range**[a]	**Avg.**	**Range**	**Avg.**	**Range**	**Avg.**	**Range**
	Percent (%) of aboveground dry matter							
Seeding rate, seeds ha^{-1}								
123,500	12b[b]	11–13	26b	24–28	17a	16–18	45a	43–47
222,400	13b	12–13	27b	25–29	16b	15–18	44a	43–46
321,200	14a	13–14	27b	25–29	15c	14–17	44a	43–45
420,100	12b	12–13	29a	26–32	14 d	12–16	45a	44–46
P > *F*	.02		.03		<.01		.52	
Fertilizer								
Non-fertilized	13a	13–14	26c	25–29	17a	15–18	44a	43–47
MOP[c]	13a	12–14	27b	25–29	16ab	15–17	44a	44–45
MESZ[d]	12a	12–14	28a	26–31	15c	14–17	45a	43–46
MOP + MESZ	13a	12–14	28a	26–29	15bc	14–17	44a	43–45
P > *F*	.88		.02		<.01		.98	

[a] Range represents the least and greatest values observed across all site-years.
[b] Values followed by the same letter are not significantly different at α = .10.
[c] MOP: muriate of potash (0–0–62 N–P–K).
[d] MESZ: MicroEssentials SZ (Mosaic Co.) (12–40–0–10–1 N–P–K–S–Zn).

Grain HI was not affected by seeding rate or fertilizer treatment and ranged between 43–47% (Table 7). Similar R8TDM and grain HI in seeding rates between 123,500 and 420,100 seeds ha^{-1} suggested no differences in yield should be expected (Table 7). Comparison of machine-harvested grain HI with hand-harvested grain R8TDM indicated approximately 1247 kg ha^{-1} (24%) of grain was not collected at the 123,500 seeds ha^{-1} rate. Grower management options that result in flatter ground conditions (e.g., less aggressive row cleaners at planting, rolling fields with larger stones near the surface after planting, or reduced surface crop residue) may address challenges of branch and pod production close to the soil surface at reduced seeding rates (i.e., 123,500 seeds ha^{-1}) (Quick & Buchele, 1974; Berglund & Helms, 2003). Despite the increased potential for grain loss at reduced seeding rates (i.e., 123,500 seeds ha^{-1}) due to branching closer to the soil surface (Lueschen & Hicks, 1977), growers should fertilize for full yield potential.

3.4 | Grain yield

Grain yield indicated significant seeding rate ($P < .01$) and fertilizer treatment ($P < .01$) main effects but no interaction between site-year and treatments ($P = .34$) (Table 8). Mean grain yields ranged from 3.39 to 3.81 Mg ha^{-1} with no statistical differences above 222,400 seeds ha^{-1}. Increasing seeding rate from 123,500 to 222,400 seeds ha^{-1} improved grain yield by 310 kg ha^{-1}. Between the two lowest seeding rates in the current study, increasing the seeding rate 80% only resulted in 9% greater yield indicating interplant competition for light, water, and nutrients may have contributed to the lack of proportioned grain yield increases at greater seeding rates (i.e., >222,400 seeds ha^{-1}) (Duncan, 1986; Egli, 1988b; Walker et al., 2010). At lower than recommended seeding rates (i.e., <321,200 seeds ha^{-1}), soybean may compensate

TABLE 8 Seeding rate and fertilizer application effects on soybean grain yield[a] and economic return[b], across locations and years, Richville and Lansing, MI, 2017–2018

Treatment	**Grain yield**	**Economic return**
	kg ha^{-1}	US$ ha^{-1}
Seeding rate, seeds ha^{-1}		
123,500	3390b[c]	959b
222,400	3700a	1037a
321,200	3700a	980b
420,100	3810a	970b
P > *F*	<.01	.04
Fertilizer		
Non-fertilized	3510b	1008ab
MOP[d]	3560b	969bc
MESZ[e]	3770a	1017a
MOP + MESZ	3750a	952c
P > *F*	<.01	.08

[a] Grain yield adjusted to 135 g kg^{-1} moisture.
[b] Economic return calculated as (soybean price x yield) minus partial budget costs.
[c] Values followed by the same letter are not significantly different at α = .10.
[d] MOP: muriate of potash (0–0–62 N–P–K).
[e] MESZ: MicroEssentials SZ (Mosaic Co.) (12–40–0–10–1 N–P–K–S–Zn).

for reduced plant densities by increasing individual plant DM production including branching, pods, and seed production (Cox, Cherney, & Shields, 2010; Suhre et al., 2014). In the current study, similar pods m^{-2} (P = .46, data not shown) between seeding rates indicated soybean plants were able to compensate for a lower population (i.e., 123,500 seeds ha^{-1}) by producing greater numbers of pods and branches per plant. Decreased seeding rates (e.g., 123,500 seeds ha^{-1}) can produce greater lateral branching and pods closer to the soil surface (Lueschen & Hicks, 1977; Carpenter & Board, 1997a; Suhre et al., 2014), which may help explain the 24% grain loss at 123,500 seeds ha^{-1} due to machine harvest difficulties and the 9% yield difference between the 123,500 and 222,400 seeds ha^{-1} seeding rates. Additionally, greater sinks (e.g., pods) plant^{-1} competing for available water and nutrients under normal to deficit July−September precipitation may have contributed to the yield reduction observed at 123,500 seeds ha^{-1} (Egli et al., 1985). Decreased seeding rates (i.e., <222,400 seeds ha^{-1}) may be supported under adequate moisture, but crop stress during pod formation and grain-fill likely impacted grain yield potential in this study (Egli et al., 1983; Prasad, Staggenborg, & Ristic, 2008).

When averaged across locations and years, grain yield was affected by fertilizer application (P < .01) (Table 8). Compared to the non-fertilized treatment, MESZ and MOP+MESZ applications increased grain yield 260 and 240 kg ha^{-1}, respectively. Current trial (<3800 kg ha^{-1}) and Michigan (3228 kg ha^{-1}) average soybean grain yields are below the suggested threshold for high-yield levels (i.e., 4500 kg ha^{-1}) indicating grain yield response to N applications would be unlikely (Salvagiotti et al., 2008; USDA-NASS, 2018a). However, correlation analysis indicated a positive relationship between V4DM and grain yield (r = .41, P < .01) suggesting the N component in MESZ may have increased both V4DM and subsequently grain production. Sufficient soil test P concentrations (i.e., 23–49 mg kg^{-1}) indicate a positive grain yield response to P application was not likely (Warncke et al., 2009). However, the delayed S availability from elemental S within MESZ may explain the increased grain S accumulation as 58% of grain S may be contributed through soil S sources after the R5.5 growth stage (Sutradhar et al., 2017; Gaspar et al., 2018). Additionally, pre-plant soil nutrient analysis indicated soil Zn concentrations were below critical levels and an additional 0.1 to 7.4 kg Zn ha^{-1} were recommended to support soybean growth (Warncke et al., 2009). Grain yield responses to MOP were not observed presumably due to sufficient soil test K concentrations at all locations. Significant reliance of grain K on vegetative remobilization as compared to continued soil uptake during grain-fill emphasizes the importance of maintaining pre-plant and mid-season soil K levels for soybean production (Mallarino, Webb, & Blackmer, 1991; Clover & Mallarino, 2013; Gaspar et al., 2017b). Although grain yield is influenced by environmental conditions (i.e., precipitation and temperature), maintaining sufficient soil nutrient concentrations allows growers to capitalize on grain yield potential when favorable growing conditions occur. However, growers should continue to justify fertilizer applications with soil and plant analysis, diagnostic tools, and integrated pest management rather than rely upon preventative management (Quinn & Steinke, 2019).

The positive relationship between V4DM and grain yield (r = .41, P < .01) in the current study suggests increased early-season DM helped maintain grain yield potential when limited by precipitation. During cool spring soil and air temperatures in the northern soybean production region, early-planted soybean (i.e., planted prior to 8 May) may benefit from increased early-season DM through increased seeding rates (i.e., ≥222,400 seeds ha^{-1}) and subsurface MESZ applications (Hankinson et al., 2015). However, crop growth acceleration at R1 coupled with environmental factors that inhibit plant development (i.e., deficit precipitation) may negate benefits of increased early-season DM. In the current study, correlation analysis indicated a weak relationship between grain yield and R8TDM (r = .32, P < .01) suggesting DM accumulation rate and timing of accelerated growth may influence grain yield more than TDM at maturity. Previous research has indicated both positive and negative relationships between grain yield and R8TDM. Shibles and Weber (1966) found grain yield and TDM to be independent due to environmental factors (e.g., temperature and precipitation) which influence vegetative DM much earlier than grain formation. However, Gaspar et al. (2017a) suggested TDM accumulation and grain yield were positively correlated due to grain being a primary factor of TDM. In a short-season production system (e.g., July planted or double-cropped systems), Ball et al. (2000) reported seed number determination occurred prior to R5. Therefore, conditions affecting DM accumulation also affected grain yield resulting in a positive relationship (Ball et al., 2000). Trial results support previous research suggesting environmental conditions encountered during soybean reproductive stages may greater influence grain yield than those during vegetative DM accumulation (Prasad et al., 2008).

Gaspar et al. (2017a) reported DM accumulation post-R5 was 32 and 22% in high (i.e., 5500 kg ha^{-1}) and low (i.e., 3600 kg ha^{-1}) yield potentials, respectively, suggesting that increased grain yields were associated with greater late-season DM accumulation. In the current study, treatments associated with greater yield (i.e., ≥222,400 seeds ha^{-1} and MESZ applications) obtained 25–31% of DM production after R5. However, 32−40% of DM was obtained after R5 in treatments where no yield increases were observed (i.e., 123,500 seeds ha^{-1} and unfertilized and MOP application) (data not shown) suggesting that despite few differences in overall R8TDM across treatments, greater DM production early rather than later in the season may allow the plant to partition greater photosynthate to grain. Continued DM accumulation between R5 and R8 increased canopy greenness 5–7 d (visual observation) which may improve the photosynthetic capacity (i.e., "stay-green" potential) and duration of grain-fill. Although a protracted grain-fill period may increase yield potential, soybean maturity and subsequent planting of autumn-seeded small grains (e.g., winter wheat [*Triticum aestivum* L.]) may be delayed (Egli, 2004). As forecasts predict more intense rainfall periods followed by extended periods of drought, unpredictable drought frequencies, and deficit July and August precipitation trends across the north-central United States, the importance of increasing early-season DM to maintain soybean grain yield potential may increase (Ham, Liener, Evans, Frazier, & Nelson, 1975; Karl et al., 2009).

3.5 | Economic analysis

Net economic return at 2017–2018 soybean prices ($351.27 and $318.57 Mg^{-1} in 2017 and 2018, respectively) was not influenced by location or year ($P = .25$) and data were presented by seeding rate and fertilizer treatments (Table 8). Net economic return was maximized at 222,400 seeds ha^{-1} and decreased both above and below this seeding rate. A quadratic model describing yield and net return response to seeding rate was fit to the data and suggested maximum grain yield was achieved at 364,300 seeds ha^{-1} while net economic return was maximized at 265,300 seeds ha^{-1}. Growers often identify grain yield potential as a greater risk factor instead of profitability (Rutan & Steinke, 2018). Without improvements to commodity prices, results from this study suggest growers may want to consider incrementally decreasing seeding rates to <321,200 seed ha^{-1} for increased profitability instead of maximizing yield.

Net economic return ($P = .08$) was affected by fertilizer application (Table 8). Compared to the non-fertilized control, the combination of MOP and MESZ reduced profit $56 ha^{-1} and emphasized the risk of profit loss when nutrient application occurs to soils with above critical nutrient concentrations. Within the environments evaluated, no profitability differences were observed between the non-fertilized treatment and MESZ application indicating the grain yield increase from MESZ was not large enough to offset both product and application costs. The lack of visual plant nutrient deficiencies combined with sufficient soil test concentrations indicated an economic response to fertilizer application was unlikely (Warncke et al., 2009; Sutradhar et al., 2017). Economic profitability is a component of longer-term sustainability, but increases in grain yield must be considered alongside soil test nutrient concentrations and crop-specific nutrient responsiveness prior to implementing fertilizer strategies.

4 | CONCLUSIONS

Soybean seeding rate and fertilizer application are two factors that can influence early-season plant growth which may provide opportunities to improve nutrient uptake and grain yield. Seeding rates ≥222,400 seeds ha^{-1} and 5 × 5 MESZ fertilizer applications effectively increased early-season DM, plant nutrient accumulation, and grain yield. Although a positive relationship between V4DM and grain yield suggests early-season nutrient management offers opportunities to enhance grain yield, additional early-season plant growth did not always translate into increased grain yield especially when soil nutrient concentrations were at or above critical concentrations. Seeding rate and fertilizer application significantly affected R8TDM partitioning to stems/petioles and flowers/pods but had minimal effects on grain. Sulfur grain nutrient accumulation was the only nutrient affected by fertilizer treatments in the current study. To promote a durable and resilient soybean agroecosystem, seeding rates that maximize DM accumulation (i.e., ≥222,400 seeds ha^{-1}) may also facilitate nutrient uptake which may play a larger role in critically impaired watersheds or regions of greater nutrient loss potential. Economic analysis (i.e., optimal profit and yield obtained at 265,000 and 364,000 seeds ha^{-1}, respectively) indicated profit consideration may outweigh yield and TDM when selecting seed rates for economic efficiency. Both potential yield response and long-term fertilizer investments (i.e., build and maintain fertilizer philosophies) that sustain soil nutrient concentrations and support plant growth should be considered in lieu of broadly implemented, singular management regimes. Future research which includes additional fertilizer applications, row spacings, and planting dates under a variety of environmental conditions will provide additional data for enhancing site-specific soybean DM and nutrient management.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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