Received: 9 June 2021 | Accepted: 10 September 2021 | Published online: 27 October 2021

DOI: 10.1002/agj2.20889

Agronomy Journal

ARTICLE

Crop Economics, Production, and Management

Foliar fertilizers rarely increase yield in United States soybean

Emma G. Matcham[1] | R. Atwell Vann[2] | Laura E. Lindsey[3] | John M. Gaska[1] | Dylan T. Lilley[2] | W. Jeremy Ross[4] | David L. Wright[5] | Carrie Knott[6] | Chad D. Lee[7] | David Moseley[8] | Maninder Singh[9] | Seth Naeve[10] | J. Trenton Irby[11] | William Wiebold[12] | Hans Kandel[13] | Josh Lofton[14] | Matthew Inman[15] | Jonathon Kleinjan[16] | David L. Holshouser[17] | Shawn P. Conley[1]

[1] Dep. of Agronomy, Univ. of Wisconsin–Madison, Madison, WI, 53706, USA

[2] Dep. of Crop and Soil Sciences, NC State Univ., Raleigh, NC, 27695, USA

[3] Dep. of Horticulture and Crop Science, The Ohio State Univ., Columbus, OH, 43210, USA

[4] Cooperative Extension Service, Univ. of Arkansas System, Division of Agriculture, Little Rock, AR, 72204, USA

[5] Dep. of Agronomy, Univ. of Florida, North Florida Research and Education Center, Quincy, FL, 32351, USA

[6] Dep. of Plant and Soil Sciences, Univ. of Kentucky, Princeton, KY, 42445, USA

[7] Dep. of Plant and Soil Sciences, Univ. of Kentucky, Lexington, KY, 40506, USA

[8] Dean Lee Research and Extension Center, LA State Univ., Alexandria, LA, 71302, USA

[9] Dep. of Plant, Soil and Microbial Sciences, MI State Univ., Lansing, MI, 48824, USA

[10] Dep. of Agronomy and Plant Genetics, Univ. of Minnesota, St. Paul, MN, 55108, USA

[11] Dep. of Plant and Soil Sciences, MS State Univ., Mississippi State, MS, 39762, USA

[12] Division of Plant Sciences, Univ. of Missouri, Columbia, MO, 65211, USA

[13] Dep. of Plant Sciences, ND State Univ., Fargo, ND, 58105, USA

[14] Dep. of Plant and Soil Sciences, OK State Univ., Stillwater, OK, 74078, USA

[15] Pee Dee Research and Education Center, Clemson Univ., Florance, SC 29506, USA

[16] Dep. of Agronomy, Horticulture, and Crop Science, SD State Univ., Brookings, SD, 57007, USA

[17] Dep. of Crop and Soil Environmental Sciences, Virginia Polytechnic Institute and State Univ., Tidewater Research Station, Suffolk, VA, 23437, USA

Correspondence
Emma G. Matcham, Dep. of Agronomy, Univ. of Wisconsin–Madison, Madison, WI, 53706, USA.
Email: matcham@wisc.edu

Assigned to Associate Editor Suduan Gao.

Abstract

Farmers have been interested in using foliar-applied nutrient products to increase soybean [*Glycine max* (L.) Merr.] yield since at least the 1970s, despite limited evidence that these products offer consistent yield increases when used prophylactically. Recently, interest in foliar fertilizer products for soybean production has been renewed, likely related to elevated soybean prices. Over the 2019 and 2020 growing seasons (46 site-years), agronomists in 16 states collaborated to test six foliar nutrient treatments (commercial mixtures of macro- and micro-nutrients) on soybean grain yield and composition. Soybean grain yield and composition differed among sites but not among foliar fertilizer treatments. Results show that prophylactic

Abbreviations: NIR, near-infrared spectroscopy.

foliar fertilization is likely to decrease the profitability of soybean production. Foliar fertilizer products tested in this study and similar products should not be recommended to U.S. soybean farmers in the absence of visual symptoms of nutrient deficiency.

1 INTRODUCTION

Annual soybean [*Glycine max* (L.) Merr.] production in the United States varied between 97 and 121 billion kilograms between 2015 and 2020 (USDA-NASS, 2021b). Many soybean farmers are interested in foliar products that apply a mixture of micronutrients and macronutrients and can be tank-mixed with insecticides and fungicides and applied during reproductive growth. This timeline corresponds with a period of high nutrient uptake for soybean (Gaspar et al., 2017). There has been interest in testing different fertilizer methods that may increase soybean yield as the United States has reached record high soybean yields, since some farmers are concerned that fields with higher yields may need nutrients supplied at different times or in different forms. Recently, questions regarding foliar fertilizers have been increasing. Thus, interest in foliar fertilizer products for soybean production has been renewed.

Past foliar fertilizer research has shown inconsistent impacts on soybean yield. In the 1970s, a study in Iowa associated up to 538 kg ha^{-1} yield increases to foliar application of N, P, K, and S in combination, while a similar study in Wisconsin reported no yield increase in soybean yield with P, K, and S foliar applications and a smaller yield increase when N was applied foliarly (Garcia & Hanway, 1976; Syverud et al., 1980). A contemporaneous study in Minnesota showed a yield benefit to N–P–K–S foliar fertilization in only 1 out of 16 trial site-years, and no yield benefit to micronutrient application (Poole et al., 1983).

Larger studies in the 1990s in Iowa showed small, inconsistent increases in yield with early-season prophylactic foliar fertilizer application. Treatments contained N, P, and K and increased yield as compared to untreated controls by 30–60 kg ha^{-1} at 10 of the 48 site-years (Haq & Mallarino, 1998). In a subsequent on-farm strip trial, comparing an untreated control to soybean treated with 1.2 kg N, 3.1 kg P, and 5.9 kg K (elemental rate per hectare) during reproductive growth, there was a 35 kg ha^{-1} increase in soybean yield at one out of eight sites (Mallarino et al., 2001). The associated small-plot trial tested a wider range of nutrient rates and had two responsive locations out of 18 with a 93–360 kg ha^{-1} increase in soybean yield when N, P, and K were applied (Mallarino et al., 2001).

Agronomists in Michigan have performed extensive foliar fertilizer trials in soybean since 2000. Out of the 51 location N–P–K product trials, four locations had increased yield and the fertilized plots had lower profitability than the unfertilized control at all locations. Foliarly applied N alone in 18 Michigan trials resulted in higher yield in three trial locations (Staton, 2019).

Prophylactic application of micronutrients has shown similarly minimal effects on soybean yield. Between the 1980s and today, trials in Iowa, Minnesota, and Michigan have not shown a yield increase in soybean associated with Fe, Zn, B, Co, Cu, Zn, Mn, or Mo foliar prophylactic application (Mallarino et al., 2001; Poole et al., 1983). Rare response to micronutrients has been observed in Ohio, where <2% of Mn trials have seen an increase in yield when fertilizer was applied and <5% of trials treated with a mixture of Mn, Fe, Cu, Mo, and B fertilizers had an observed soybean yield increase (Sharma et al., 2018). In Michigan fields with high pH lakebed soils that are likely to respond to Mn application, foliar Mn application only increased yield when it was applied after visual symptoms of nutrient deficiency began, but not when Mn was applied prophylactically (Staton, 2019).

One challenge to assessing the efficacy of foliar fertilization in soybean is that when yield increases have been observed, the magnitude of yield improvement is relatively small and generally does not pay for the cost of application. Additionally, it is difficult to identify field conditions where agronomists should recommend foliar fertilizer application in soybean because past studies have shown that soybean yield response to foliar fertilizer is inconsistent. Despite the lack of evidence that soybean yield and farm profit increase with prophylactic foliar nutrient application in the United States, these products are still commonly marketed for soybean in the United States.

Past foliar fertilization in soybean research in the United States has been isolated to a few states in the upper Midwest (Iowa, Wisconsin, Michigan, and Ohio). This study is a coordinated effort across 16 states (Arkansas, Florida, Kentucky, Louisiana, Michigan, Minnesota, Missouri, Mississippi, Ohio, Oklahoma, North Carolina, North Dakota, South Carolina, South Dakota, Wisconsin, Virginia) that allowed us to test the effects of macronutrient and micronutrient foliar fertilization throughout the primary soybean-producing region of the United States and includes a broad range of commercially available foliar fertilizer products to assess the efficacy of both macronutrient and micronutrient applications. The objectives of this study were to (a) identify soybean grain yield response to prophylactic foliar fertilizer application across a broad range of environments, (b) determine if foliar fertilizer application changes soybean grain composition, and (c) conduct economic analyses on the value of these products in U.S. soybean-growing environments.

Core Ideas

- The tested prophylactic foliar fertilizers did not increase soybean yield.
- Foliar fertilizers did not change grain composition.
- Prophylactic foliar fertilizers tested decreased profitability.

2 | METHODS

2.1 | Field methods

In 2019 and 2020, small-plot trials were established at a total of 46 sites in 16 states (Figure 1). Six foliar nutrient products (Table 1) and the untreated control were applied in a randomized complete block design with four to eight replications depending on site. Products were selected with the input of industry professionals to identify foliar fertilizers that are nationally marketed to soybean producers. Products were applied at soybean growth stage R3 to align with commonly used fungicide and insecticide application timing. Growth stage R3 was defined by one pod of at least 5 mm in length on one or more of the top four nodes of the plant (University of Wisconsin-Extension, 2017). Due to lack of product availability, HarvestMore UreaMate was not applied in Lexington, KY, in 2019 and Smart Quatro Plus was not applied at any 2019 Wisconsin sites and the Arlington, WI, site in 2020.

Composite soil samples were taken from each replication at each site in the spring. Samples were air-dried, and soil physical and chemical properties were measured by A&L Great Lakes (Fort Wayne, IN). Soil sample results and site management practices can be found in Supplemental Table S1.

Backpack sprayers were used to to apply foliar fertilizers at the R3 growth stage. Visual symptoms of nutrient deficiency were not present at any site prior to foliar fertilizer application.

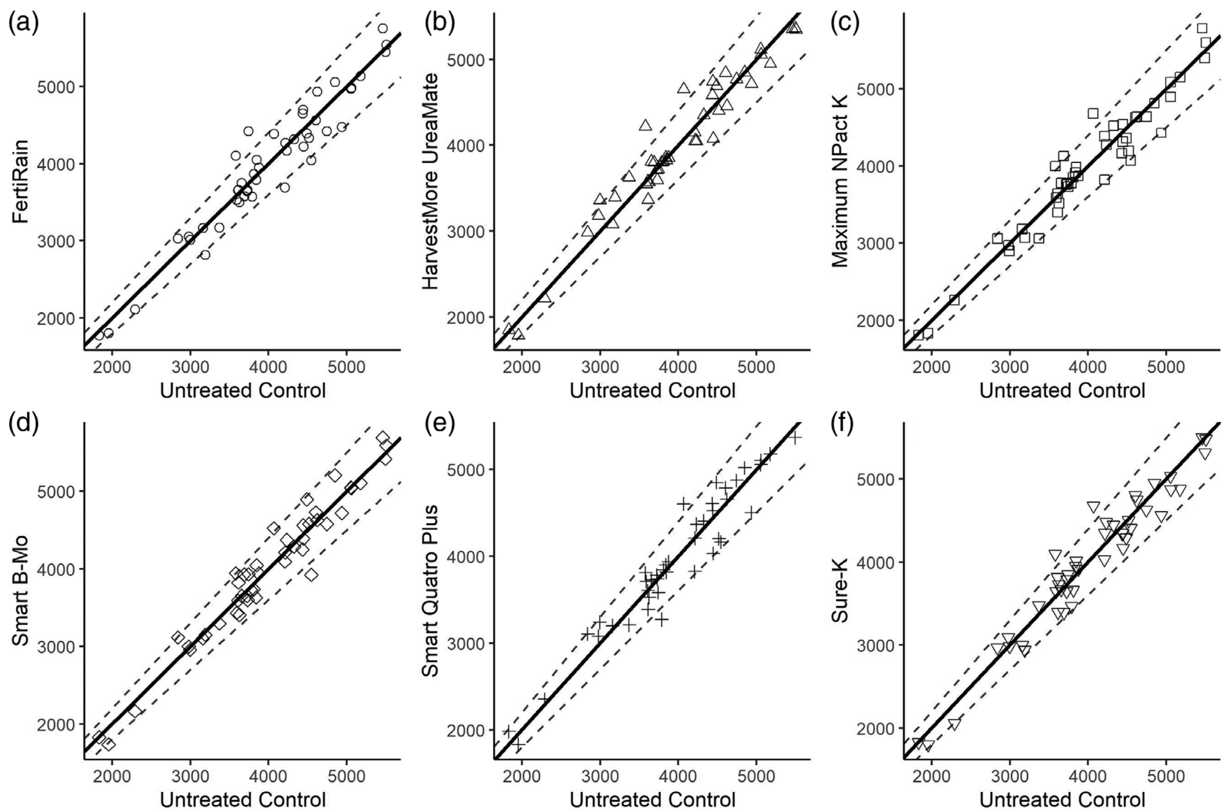

FIGURE 1 Average yield (kg ha^{-1}) at each site for each treatment plotted against the average yield of the untreated control at the same site. Solid lines represent $x = y$, and the dashed lines represent ±10% of yield. (a) Average yield of plots treated with FertiRain compared to Untreated Control plots, (b) average yield of plots treated with HarvestMore UreaMate compared to Untreated Control plots, (c) average yield of plots treated with Maximum NPact K compared to Untreated Control plots, (d) average yield of plots treated with Smart B-Mo compared to Untreated Control plots, (e) average yield of plots treated with Smart Quatro Plus compared to Untreated Control plots, and (f) average yield of plots treated with Sure-K compared to Untreated Control plots

TABLE 1 List of foliar products names, application rate, cost of product, and nutrients applied for each treatment

Treatment name	Manufacturer	Application rate	Cost of product	N	P	K	S	Mn	Fe	Mo	Zn	B	Other
			US\$ ha^{-1}	kg ha^{-1}									
FertiRain	AgroLiquid	28.0 L ha^{-1}	\$55	3.1	1.0	1.0	0.6	0.02	0.03	–	0.03	–	–
Sure-K	Agroliquid	28.0 L ha^{-1}	\$48	0.7	0.3	1.0	–	–	–	–	–	–	–
HarvestMore Ureamate	Stoller	2.8 kg ha^{-1}	\$12	0.1	0.3	–	–	0.01	–	0.002	0.01	–	Ca, Mg, B, Co, Cu
Smart B-Mo	Brandt	1.2 L ha^{-1}	\$9	–	–	–	–	–	–	0.007	–	0.08	–
Smart Quatro Plus	Brandt	4.7 L ha^{-1}	\$16	–	–	–	0.04	0.09	–	0.003	0.09	0.07	–
Maximum NPact K	Nutrien	14.0 L ha^{-1}	\$52	2.1	–	2.1	–	–	–	–	–	–	–
Untreated Control	–	–	–	–	–	–	–	–	–	–	–	–	–

Selected application rates (Table 1) were within the range of rates recommended on each product's label. Leaf tissue samples were taken before foliar products were applied at R3 and 2 wk following application. At both sampling time points, the newest fully-expanded trifoliate leaf was collected from 20 plants per plot. Samples were dried in paper bags (dryer temperature 38–54 ˚C) until constant weight was achieved and shipped to the North Carolina Department of Agriculture & Consumer Services Agronomic Division (Raleigh, NC) for analysis of N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, and B. The North Carolina Department of Agriculture Agronomic Division's Plant Tissue lab measures N using oxygen combustion with gas chromatography, NO_3^-–N using an electrode, and all other nutrients using HNO_3 closed vessel microwave digestion followed by inductively coupled plasma (ICP). Tissue samples were taken from all sites in 2020 but were not collected at seven sites in 2019: Newport, AR; Pine Tree, AR; Florida; Princeton, KY; Missouri; Minnesota Lake, MN; and Danvers, MN.

Yield data were collected using plot combines at each site and adjusted to 130 g kg^{-1} moisture concentration. Grain samples were taken at harvest from all sites except in Missouri in 2019; Oklahoma in 2020; and Hoytville, OH, in 2020. In 2019, grain protein and oil concentration were analyzed via near-infrared spectroscopy (NIR) using a Perten DA7520 machine. The NIR calibration curve was developed from hundreds of soybean samples with known composition values (Soybean NIR Consortium). In 2020, grain protein and oil were determined using the Perten Instruments Inframatic 9500 NIR Grain Analyzer. Calibration curves were provided and validated by Perten and were normalized using a polystyrene reference standard. Grain protein and oil concentration were reported at a standard moisture of 130 g kg^{-1}.

Cost of foliar fertilizer products were assessed by calling retailers in the study region in 2019 and averaging the cost of product per hectare at the application rate used in the study (Table 1). Partial profits were calculated by multiplying yield by the price of soybean grain and subtracting the cost of the foliar fertilizer product. Application costs were not considered since these products are frequently applied by farmers as part of a tank-mix with foliar fungicides and insecticides. Calculations were performed at \$0.550 and \$0.367 kg^{-1} to be reflective of recent soybean prices (USDA-NASS, 2021a).

2.2 | Analysis methods

Change in tissue nutrient concentration was calculated by subtracting nutrient concentration from the pre-application samples from the nutrient concentration from the 2 wk post-application samples. Yield, protein, oil, and change in tissue nutrient concentration values that fell outside of three standard deviations of each site's mean value were considered outliers and removed from further analysis. Yield data was collected for 1,868 plots in total, and 34 of those observations (<2%) were considered outliers and removed from further analysis because they fell outside of three standard deviations of each site's mean yield.

Mixed-model ANOVA was performed using R 3.6.2 and the package *lme4*. All site-years were analyzed together with treatment and site-year considered fixed variables, and replication nested within site-year being considered a random variable. Throughout the manuscript, site-years will be referred to as "site." Degrees of freedom were estimated using Kenward–Rogers approximation to account for unequal replication among site years. Data were not transformed, and residuals were plotted to assess for normality. Means comparisons were performed using Bonferroni adjustments.

3 | RESULTS AND DISCUSSION

3.1 | Soybean grain yield

In 2019, the highest-yielding site was Arlington, WI (5,513 kg ha^{-1}) and the lowest-yielding site was Yadkin, NC (1,824 kg

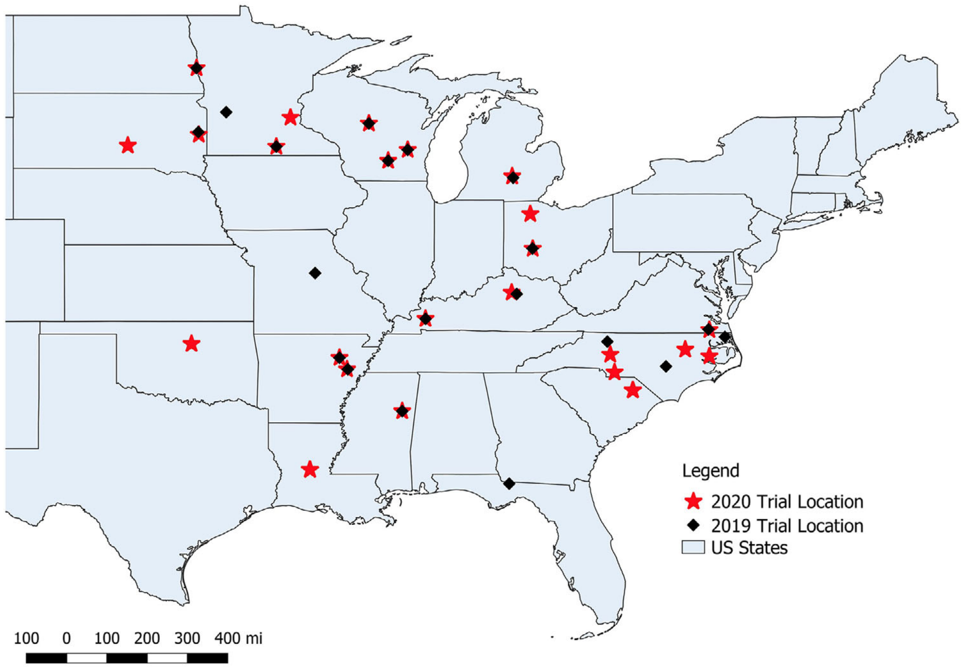

FIGURE 2 Trial locations in 2019 and 2020, displayed with red stars and black diamonds, respectively. South Carolina and Louisiana have two nearby sites each that appear as a single marker due to the scale of this map

ha^{-1}). Yields were overall higher in 2020, with the highest yields observed at Arlington, WI (5,592 kg ha^{-1}). Figure 2 compares site average yield for each treatment to the control at each site, and additional summaries of site mean yield are available in Supplemental Table S2. Most observations fall near or on the 1:1 line (Figure 2), indicating that the treated plots and untreated control plots yielded similarly. The few points that fell above the 10% yield increase line tended to have yields near 4,000 kg ha^{-1}. All sites with yields higher than 5,000 kg ha^{-1} had mean treated plot yield within 10% of the untreated control plots for all foliar fertilizer products (Figure 2). Observed differences in yield among treatments were not statistically significant (F = 0.23, p = .9663), although there was a significant difference in yield among sites. There was not a significant interaction between site and treatment (Table 2).

An additional ANOVA model was run to determine whether low- (<3,000 kg ha^{-1}), medium- (3,000–4,000 kg ha^{-1}), or high-yielding (>4,000 kg ha^{-1}) sites responded to treatment differently, with sites grouped into yield environments based on the average yield of the untreated control. All site-years were analyzed together with treatment and yield environment considered fixed variables, and site-year nested within yield environment and replication nested within site-year and yield environment being considered random variables. This model confirmed that there were neither differences in yield among treatments (F = 0.44, p = .8532), nor an interaction between treatment and yield environment (F = 0.89, p = .5540).

TABLE 2 Results from analysis of variance used to identify differences in yield, protein, and oil based on treatment, site, and their interaction

Measured variable	Fixed effect	F value	p value
Yield	Treatment (T)	0.23	.9663
	Site (S)	61.05	<.001
	T × S	1.00	.4812
Protein	Treatment (T)	1.37	.2248
	Site (S)	557.92	<.001
	T × S	1.15	.0703
Oil	Treatment (T)	1.62	.1382
	Site (S)	392.72	<.001
	T × S	1.17	.0490

The sites tested in this trial include a wide range of soil chemical and physical properties (Supplemental Table S1). Even at sites such as Princeton, KY (2019 and 2020) and North Dakota (2019) where soil test P concentration was below 15 mg kg^{-1}, there was not a yield response to treatment. Site soil pH ranged from 4.7 to 8.3, but sites did not have significant differences in response to nutrient application even though high pH can reduce micronutrient availability. Given the uniformity of the response across these 46 sites, there is no evidence that foliar fertilizers increase soybean yield in the absence of visual symptoms of nutrient deficiency. Similar results were observed in a smaller geographic area

TABLE 3 Results from analysis of variance used to identify differences in leaf nutrient concentration based on treatment, site, and the interaction of site and treatment

	N		P		K		Ca		Mn	
Fixed effect	***F* value**	***p* value**	***F* value**	***p* value**	***F* value**	***p* value**	***F* value**	***p* value**	***F* value**	***p* value**
Treatment (T)	1.20	.3037	0.89	.5029	1.28	.2614	0.63	.7026	0.94	.4666
Site (S)	31.37	<.001	3.28	<.001	5.92	<.001	39.39	<.001	47.42	<.001
T × S	0.82	.9673	1.18	.0565	1.19	.0422	0.98	.5522	1.18	.0489
	S		Fe		Mn		Cu		B	
	F value	*p* value	*F* value	*p* value	*F* value	*p* value	*F* value	*p* value	*F* value	*p* value
Treatment (T)	0.55	.7728	1.62	.1368	2.58	.0174	6.86	<.001	40.16	<.001
Site (S)	27.29	<.001	14.50	<.001	16.56	<.001	21.84	<.001	52.65	<.001
T × S	1.00	.4994	1.00	.5019	0.78	.9875	1.24	.0168	2.28	<.001

TABLE 4 Results from analysis of variance used to identify differences in partial profits based on treatment, site, and the interaction of site and treatment

Measured variable	**Fixed effect**	***F* value**	***p* value**
Profit at soybean grain price of $0.550 kg^{-1}	Treatment (T)	5.74	<.001
	Site (S)	59.31	<.001
	T x S	1.01	.4396
Profit at soybean grain price of $0.367 kg^{-1}	Treatment (T)	5.74	<.001
	Site (S)	59.31	<.001
	T x S	1.01	.4396

in past trials from Iowa and Michigan, where micronutrient and macronutrient foliar fertilization did not consistently increase soybean grain yield (Mallarino et al., 2001; Staton, 2019).

3.2 | Grain composition

Grain samples from each plot were collected in 19 sites in 2019 and 24 sites in 2020. Average protein and oil content across all sites and treatments was 376 and 206 g kg^{-1}, respectively. Differences in grain protein and oil content were observed among sites but not treatments (Table 2). Most sites had similar oil content across all treatments, but there was a treatment × site interaction related to two differences between sites: the Ohio 2019 site had approximately 0.5% higher average oil content in the untreated control and FertiRain-treated plots and the Sampson, NC, 2019 site had slightly lower oil content in the plots treated with Sure-K as compared with other treatments. At nutrient application rates currently recommended by foliar fertilizer manufacturers, there is no evidence that fields that receive foliar fertilizer should be expected to have different grain protein or oil content as compared to fields that do not receive foliar fertilizer.

3.3 | Leaf nutrient content

Across all sites and treatments, average leaf tissue Ca, Mn, and B concentration increased by 1.5, 78, and 19 g kg^{-1}, respectively, between the pre-application sampling timepoint and the 2 wk after application timepoint (Supplemental Table S3). Leaf tissue S concentration did not change between sampling timepoints. Concentration of N, P, K, Mg, Fe, and Cu decreased slightly (<10 g kg^{-1}) between the pre-application sampling timepoint and the 2 wk after application timepoint, likely due to soybean plants partitioning an increasing proportion of their nutrient uptake to seeds relative to other plant parts after R4 (Gaspar et al., 2017). Observed decreases in tissue nutrient concentrations were <10 g kg^{-1} on average, with the exception of Fe which decreased by an average of 70 g kg^{-1} between the sampling timepoints.

Across all nutrients tested (N, P, K, Ca, Mg, S, Fe, Mn, Cu, and B), there was a significant difference in leaf tissue nutrient content among sites (Table 3). Leaf tissue Mn, Cu, and B content varied among treatments (Table 3). While past studies indicate that fields with low leaf tissue P concentration may be more likely to see a yield response to foliar fertilization (Haq & Mallarino, 1998), foliar fertilizer treatments in our study and others did not necessarily cause differences in leaf tissue nutrient concentrations for most nutrients. Application of micronutrients such as Cu and B are more likely to result in differences in leaf tissue micronutrient concentration. Application of P frequently does not change leaf tissue P concentration (Alt et al., 2018; Haq & Mallarino, 1998; Nelson et al., 2012).

3.4 | Cost of foliar fertilizer products

Cost of foliar fertilizer products ranged from US$9 to $55 ha^{-1} (Table 1). Partial profits were different among treatments and sites at both tested soybean grain prices ($0.550

TABLE 5 Mean partial profit at two soybean grain prices and mean grain yield, oil concentration, and protein concentration among foliar fertilizer treatments

Treatment	Mean partial profit at soybean grain price of \$0.550 kg^{-1}	Mean partial profit at soybean grain price of \$0.367 kg^{-1}	Mean yield	Mean grain oil concentration	Mean grain protein concentration
	US\$ ha^{-1}		kg ha^{-1}	g kg^{-1}	
Untreated control	2,202 a[a]	1,470 a	4,004[b]	20.6	37.5
Smart B-Mo	2,198 ab	1,464 a	4,013	20.6	37.6
HarvestMore UreaMate	2,193 ab	1,459 a	4,008	20.5	37.6
Smart Quatro Plus	2,168 ab	1,442 ab	3,972	20.6	37.6
FertiRain	2,151 ab	1,417 b	4,012	20.6	37.5
Sure-K	2,149 ab	1,418 b	3,994	20.6	37.6
Maximum NPact K	2,142 b	1,412 b	3,990	20.6	37.6

[a]Means not sharing common letters within each column denote statistical differences among treatments (α = .05). Bonferroni adjustments were used to adjust for multiplicity.

[b]Means separation was not performed for yield or grain composition (oil and protein) due to no significant differences among treatments.

and \$0.367 kg^{-1}), and there was no interaction between treatment and site at either tested soybean grain price (Table 4). At \$0.550 kg^{-1}, plots treated with Maximum NPact K had \$60 ha^{-1} lower profits than the untreated control and at \$0.367 kg^{-1}, plots treated with Maximum NPact K or FertiRain had lower profits than the untreated control by \$58 and \$53 ha^{-1}, respectively (Table 5). While other treatments did not have statistically lower profits than the untreated control at the tested grain prices, application of foliar fertilizer products included in this study would not increase profit since foliar fertilizer treatments did not statistically increase soybean grain yield. Further reductions in profit may occur when applying foliar fertilizer using a ground-based applicator since wheel damage can reduce soybean yield by 3–5% after R1 (Hanna et al., 2008).

4 | CONCLUSIONS

Prophylactic foliar fertilizer applications did not consistently increase soybean yield or alter grain composition when applied at rates recommended by their manufacturer, and foliar fertilizer application may decrease farm profitability. None of the tested foliar fertilizer treatments had higher partial profits than the untreated control. Agronomists and farmers interested in increasing soybean yield or farm profitability are unlikely to see benefit from foliar fertilizer application in the absence of visual symptoms of nutrient deficiency.

ACKNOWLEDGMENTS

This research was funded by Soybean Checkoff funds through the Qualified State Soybean Board in each state. Additional support was provided by the United Soybean Board through the Science For Success initiative.

AUTHOR CONTRIBUTIONS

Emma G. Matcham: Formal analysis; Methodology; Project administration; Writing-original draft; Writing-review & editing. R. Atwell Vann: Conceptualization; Data curation; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Writing-original draft; Writing-review & editing.; Laura E. Lindsey: Conceptualization; Funding acquisition; Methodology; Resources; Writing-review & editing; John M. Gaska: Project administration; Resources; Writing-review & editing. Dylan T. Lilley: Data curation; Writing-review & editing. W. Jeremy Ross: Funding acquisition; Resources; Writing-review & editing. David L. Wright: Funding acquisition; Resources; Writing-review & editing. Carrie Knott: Funding acquisition; Resources; Writing-review & editing. Chad D. Lee: Funding acquisition; Resources; Writing-review & editing. David Moseley: Funding acquisition; Resources; Writing-review & editing. Maninder Singh: Funding acquisition; Resources; Writing-review & editing. Seth Naeve; Funding acquisition; Resources; Writing-review & editing. J. Trenton Irby: Funding acquisition; Resources; Writing-review & editing. William Wiebold: Funding acquisition; Resources; Writing-review & editing. Hans Kandel: Funding acquisition; Resources; Writing-review & editing. Josh Lofton: Funding acquisition; Resources; Writing-review & editing. Matthew Inman: Funding acquisition; Resources; Writing-review & editing. Jonathon Kleinjan: Funding acquisition; Resources; Writing-review & editing. David L. Holshouser: Funding acquisition; Resources; Writing-review & editing. Shawn P. Conley: Funding acquisition; Project administration; Resources; Supervision; Writing-review & editing. All authors managed plots and data collection within their respective states and contributed to writing and editing the manuscript. Dylan T. Lilley collected price data. Emma G.

Matcham, R. Atwell Vann, Laura E. Lindsey, and Shawn P. Conley coordinated data collection and planned the trial.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Emma G. Matcham https://orcid.org/0000-0002-9896-2253
Laura E. Lindsey https://orcid.org/0000-0001-7026-0949
Carrie Knott https://orcid.org/0000-0003-0379-8962
Josh Lofton https://orcid.org/0000-0002-1644-4648
David L. Holshouser https://orcid.org/0000-0002-8177-7414

REFERENCES

Alt, D., Ng, S. J., Grusenmeyer, J., & Lindsey, L. E. (2018). Seed yield and quality of transgenic high-oleic and conventional soybean as influenced by foliar manganese application. *Crop Science*, *58*(2), 874–879. https://doi.org/10.2135/cropsci2017.06.0391

Garcia, L., R., & Hanway, J. J. (1976). Foliar fertilization of soybeans during the seed-filling period. *Agronomy Journal*, *68*(4), 653–657. https://doi.org/10.2134/agronj1976.00021962006800040030x

Gaspar, A. P., Laboski, C. A. M., Naeve, S. L., & Conley, S. P. (2017). Phosphorus and potassium uptake, partitioning, and removal across a wide range of soybean seed yield levels. *Crop Science*, *57*(4), 2193–2204. https://doi.org/10.2135/cropsci2016.05.0378

Hanna, S. O., Conley, S. P., Shaner, G. E., & Santini, J. B. (2008). Fungicide application timing and row spacing effect on soybean canopy penetration and grain yield. *Agronomy Journal*, *100*(5), 1488–1492. https://doi.org/10.2134/agronj2007.0135

Haq, M. U., & Mallarino, A. P. (1998). Foliar fertilization of soybean at early vegetative stages. *Agronomy Journal*, *90*(6), 763–769. https://doi.org/10.2134/agronj1998.00021962009000060008x

Mallarino, A. P., Haq, M. U., Wittry, D., & Bermudez, M. (2001). Variation in soybean response to early season foliar fertilization among and within fields. *Agronomy Journal*, *93*(6), 1220–1226. https://doi.org/10.2134/agronj2001.1220

Nelson, K. A., Motavalli, P. P., Stevens, W. E., Kendig, J. A., Dunn, D., & Nathan, M. (2012). Foliar potassium fertilizer additives affect soybean response and weed control with glyphosate. *International Journal of Agronomy*, *2012*, 1–10. https://doi.org/10.1155/2012/461894

Poole, W. D., Randall, G. W., & Ham, G. E. (1983). Foliar fertilization of soybeans. I. Effect of fertilizer sources, rates, and frequency of application. *Agronomy Journal*, *75*(2), 195–200. https://doi.org/10.2134/agronj1983.00021962007500020010x

Sharma, S., Culman, S., Fulford, A., Lindsey, L., Alt, D., & Looker, G. (2018). *Corn, soybean, and alfalfa yield responses to micronutrient fertilization in Ohio, AGF-519*. Ohio State University Extension. https://ohioline.osu.edu/factsheet/agf-519

Staton, M. J. (2019). *Foliar fertilizer applications to soybeans are rarely profitable*. Michigan State University Extension.

Syverud, T. D., Walsh, L. M., Oplinger, E. S., & Kelling, K. A. (1980). Foliar fertilization of soybeans (*Glycine max* L.). *Communications in Soil Science and Plant Analysis*, *11*(6), 637–651. https://doi.org/10.1080/00103628009367069

University of Wisconsin-Extension. (2017). *A visual guide to soybean growth stages*. http://ipcm.wisc.edu/apps/beancam/

USDA-NASS. (2021a). *Prices received: Soybean prices received by month, US*. USDA-NASS. https://www.nass.usda.gov/Charts_and_Maps/Agricultural_Prices/pricesb.php

USDA-NASS. (2021b). Soybean production. Charts and maps. USDA-NASS. https://www.nass.usda.gov/Charts_and_Maps/graphics/soyprod.pdf

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Matcham, E. G., Vann, R., Lindsey, L., Gaska, J., Lilley, D., Ross, W. J., Wright, D. L, Knott, C., Lee, C., Moseley, D., Singh, M., Naeve, S., Irby, T., Wiebold, W., Kandel, H. J., Lofton, J., Inman, M., Kleinjan, J., Holshouser, D. L., Conley, S. P. (2021). Foliar fertilizers rarely increase yield in United States soybean. *Agronomy Journal*. *113:*5246–5253. https://doi.org/10.1002/agj2.20889