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Article

Foliar Micronutrient Application for High-Yield Maize

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Abstract: Nebraska soils are generally micronutrient sufficient. However, critical levels for current yields have not been validated. From 2013 to 2015, 26 on-farm paired comparison strip-trials were conducted across Nebraska to test the effect of foliar-applied micronutrients on maize (*Zea mays* L.) yield and foliar nutrient concentrations. Treatments were applied from V6 to V14 at sites with 10.9 to 16.4 Mg ha⁻¹ yield. Soils ranged from silty clays to fine sands. Soil micronutrient availability and tissue concentrations were all above critical levels for deficiency. Significant grain yield increases were few. Micronutrient concentrations for leaf growth that occurred after foliar applications were increased 4 to 9 mg Zn kg⁻¹ at 5 of 17 sites with application of 87 to 119 g Zn ha⁻¹, 12 to 16 mg kg⁻¹ Mn at 2 of 17 sites with application of 87 to 89 g Mn ha⁻¹, and an average of 8.1 mg kg⁻¹ Fe across 10 sites showing signs of Fe deficiency with application of 123 g foliar Fe ha⁻¹. Foliar B concentration was not affected by B application. Increases in nutrient concentrations were not related to grain yield responses except for Mn ($r = 0.54$). The mean, significant grain yield response to 123 g foliar Fe ha⁻¹ was 0.4 Mg ha⁻¹ for the 10 sites with Fe deficiency symptoms. On average, maize yield response to foliar Fe application can be profitable if Fe deficiency symptoms are observed. Response to other foliar micronutrient applications is not likely to be profitable without solid evidence of a nutrient deficiency.

Keywords: on-farm; strip-trials; micronutrients; foliar; maize; boron; manganese; iron; zinc

1. Introduction

Nebraska soils are generally micronutrient sufficient with few sites with soil and/or plant tissue samples below critical values for maize production. However, critical levels have not been validated for current yield levels. Production of 12.0 Mg ha⁻¹ of maize grain requires 1.4 kg Fe, 0.5 kg Mn, 0.5 kg Zn, and 0.08 kg B ha⁻¹ [1]. For most Nebraska soils, agronomic crops are most likely constrained from reaching their genetic and environmental potential by insufficient N and water availability [2] but other growth factors become more likely to be limiting as these factors are exceedingly met according to Julius von Liebig and Carl Sprengel's "Law of the Minimum" [3]. Thus, the likelihood of a micronutrient deficiency being the yield limiting factor then increases [4]. Maize, especially when high yielding, has high rates of nutrient uptake during the V4 to VT stage during which demand may exceed supply. Foliar application of micronutrients during this period to complement soil nutrient supply is commonly

practiced worldwide [5,6], and promoted by the fertilizer industry. Further, most foliar micronutrient supplements can be tank mixed with herbicides and pesticides, which adds to their convenience and appeal.

Plant leaves are specialized in capturing light and CO₂, but their ability to absorb nutrients has long been recognized and used in nutrient management [7]. Foliar-applied micronutrients penetrate the leaf surface through the cuticle, cuticular cracks and imperfections, stomata, trichomes, and lenticels [4]. Boron (B), manganese (Mn), iron (Fe), and zinc (Zn) are essential micronutrients of general interest to maize producers and agronomists. These micronutrients were selected for inclusion in this study based on extensive discussions with Nebraska agronomists with reference to plant tissue analysis and as a result of a soil and plant tissue survey [8].

The effectiveness of foliar micronutrient applications varies significantly in relation to their solubility and ingredients such as salts, surfactants, complexes, or chelates. When evaluating micronutrient effects, it is likely not adequate to evaluate a singular micronutrient formulation [8–11]. In an attempt to avoid this pitfall, the goal of this study is to evaluate commercial formulations, which included a variety of micronutrient mixes with a variety of additives. Past research of micronutrient foliar application on maize has had mixed results. In one study, maize grain yield was increased by nearly 18% over three years with the application of 1.0 to 1.5 kg foliar Zn ha⁻¹ [12], while many others reported no significant increase in yield [13–15].

Nutrient concentrations in plant tissue are widely used for determining the nutritional status of maize during the growing season. Deficiency of any one of the 14 essential plant nutrients can limit plant growth. Plant analysis uses this foundational concept by comparing the nutrient concentration of a particular plant part with established species-specific critical values or sufficiency ranges. A nutrient concentration below the sufficiency range or critical value implies deficiency and potential for yield response to application of the nutrient [16]. We also theorize that plants that have received micronutrient application will have greater nutrient concentrations of the applied micronutrient in new tissues, which has been demonstrated with soybeans under similar field conditions in Iowa [17].

The objective of this study is to evaluate the effect of foliar-applied micronutrients on grain yield and plant tissue nutrient concentrations under current management practices using commercially available foliar micronutrient products as guided by soil and plant tissue testing. Our hypotheses, based on responding to that approach from the field, are that (1) higher yielding sites will have a greater likelihood of yield response to micronutrient application, (2) yield response to micronutrient application will occur where foliar and soil concentrations are below critical levels or displaying deficiency symptoms of the corresponding micronutrient, and (3) applied micronutrients will increase their corresponding foliar concentration. Though we acknowledge the importance of nutrient ratios being important to yield response, this hypothesis was not investigated.

2. Materials and Methods

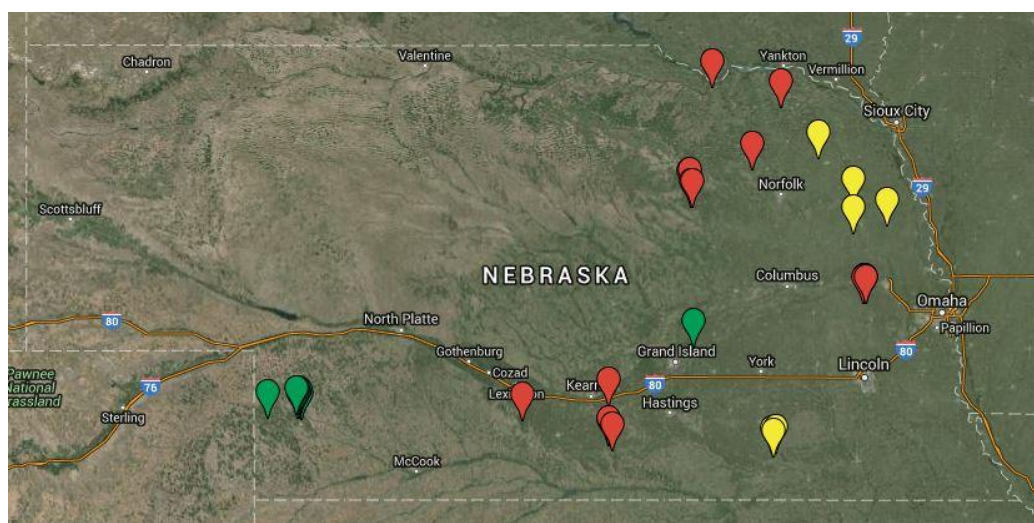
2.1. Field Sites

During 2013 to 2015, 26 paired comparison strip trials were performed across Nebraska (Table 1 and Figure 1) in order to test the effect of commercial foliar micronutrient products on grain yield. Sites were selected to be representative of Nebraska soils and encompassed 23 soil series (Table 1). The selected sites had no history of micronutrient or manure applications in the previous 10 years. Nebraska soils are generally micronutrient fertile so finding micronutrient deficient sites proved to be relatively unobtainable [18] as confirmed by a state-wide survey of soil and plant tissue samples and data obtained from Nebraska agronomic testing laboratories [8]. Preseason N applications varied by source, application time, and rate but all sites applied N at a rate sufficient for at least 12.0 Mg ha⁻¹ maize grain production [19].

Table 1. Site background information and cultural practices for 26 field strip trials testing foliar micronutrient application for irrigated maize but for popcorn at site 25 and 26.

Site	Year	County	Soil Series	Rainfall †	Till ‡	Previous Crop	Hybrid	Plant Date	Harvest Date
				mm					
1	2013	Thayer	Crete	724	NT	Soybean	Pioneer P1690HR	13-May	26-Oct
2	2013	Thayer	Crete	724	NT	Soybean	Pioneer 33D47	6-May	26-Oct
3	2013	Thayer	Crete	724	NT	Soybean	Pioneer P1690HR	7-May	26-Oct
4	2013	Wayne	Nora	902	NT	Soybean	Pioneer 1625 HR	5-May	26-Oct
5	2013	Cuming	Belfore	864	CT	Maize	Dekalb DKC61-06RIB	5-May	26-Oct
6	2013	Cuming	Belfore	953	NT	Soybean	Dekalb DK62 98 VT pro	13-May	26-Oct
7	2013	Burt	Zook	889	CT	Maize	Golden Harvest GH14R38	15-April	27-Oct
8	2014	Thurman	Thurman	673	NT	Soybean	Pioneer 1266	29-April	21-Oct
9	2014	Kearney	Boel + Valentine	711	CT	Maize	Pioneer 33D47	10-May	18-Oct
10	2014	Kearney	Holdrege + Detroit	762	CT	Maize	Pioneer 33D53 AMI	9-May	18-Oct
11	2014	Kearney	Holdrege + Detroit	762	CT	Maize	Pioneer 1469 AMI	9-May	13-Nov
12	2014	Saunders	Yutan	1016	NT	Soybean	Pioneer 1690 HR	16-May	13-Nov
13	2014	Saunders	Yutan	1016	NT	Soybean	Pioneer 1690 HR	27-April	3-Nov
14	2014	Antelope	Thurman + Nora	597	CT	Maize	Pioneer 1625 HR	15-May	19-Nov
15	2014	Antelope	Thurman + Doger	648	CT	Maize	Channel 209-53 STX RIB	27-April	26-Oct
16	2014	Antelope	Thurman + Nora	584	CT	Maize	Channel 213-40 VT3	15-May	24-Oct
17	2014	Antelope	Thurman + Doger	648	CT	Maize	Channel 213-40 VT3	25-May	26-Oct
18	2014	Cedar	Crofton + Nora	914	NT	Maize	Pioneer 1197-AM	27-April	5-Nov
19	2015	Merrick	Cozad + Alda	940	CT	Maize	Pioneer 1311-AM	25-April	9-Nov
20	2015	Chase	Blanche + Tassel-Duda	554	NT	Maize	Channel 209-69 VT3PRIB	28-April	28-Oct
21	2015	Chase	Blanche + Tassel-Duda	554	NT	Soybean	Channel 209-69 VT3PRIB	8-May	28-Oct
22	2015	Chase	Rosebud Complex	526	CT	Maize	Pioneer 1151	25-April	21-Nov
23	2015	Chase	Rosebud-Canyon	526	CT	Maize	Pioneer 1151	25-April	21-Nov
24	2015	Chase	Rosebud Complex	516	CT	Maize	Prairie Brand 5825	18-May	9-Nov
25	2015	Chase	Valent Complex	572	NT	Maize	R-98114	28-April	9-Nov
26	2015	Chase	Jayem Complex	561	NT	Wheat	R-427	2-May	20-Oct

† Observed rainfall during growing season; Rodebud complex: Rosebud-Canyon, Blanche, Duda-Tassel; Valent complex: Valent, Duda-Tassel and Jayem; ‡ Till = tillage system including conventional tillage consisting of disk or chisel plow tillage (CT) or no-till (NT); Jayem Complex: Jayem, Ascalon and Valent. Note: Row spacing was 76.2 cm except for 50.8 cm at site 5 and 18, 91.4 cm at site 19, and 38.1 cm at site 26.

**Figure 1.** Sites of the 26 on-farm strip trials color coded by year. (2013: yellow, 2014: red, 2015: green) for the study of maize response to foliar application of micronutrients.

2.2. Treatments

Sites had between three and 20 replications (i.e., strips) depending on farmer equipment and willingness (Table 2). Two of the 26 trials were on popcorn (*Zea mays everta*) (Table 1). Each of the foliar micronutrient applications were selected by the producer and their local agronomist as to best fit the micronutrient needs of each field and based on prior soil and plant tissue recommendations from commercial laboratories. No initial soil micronutrient levels were below critical levels (Ward, 2015) and no plant tissue micronutrient concentrations were below reported critical values for maize prior to tasseling [20]. Maize leaves at sites 20–24 had interveinal chlorosis (Figure 2), which can be an indication of micronutrient deficiency though plant tissue samples were above critical levels.

Table 2. Treatment micronutrient formulation and application background information for each of the 26 sites.

Site	Product †	Applied Nutrients	Rate	Elemental Rate	AM ‡	AD ‡	AD ‡	Reps
		g kg ⁻¹	L ha ⁻¹	g element ha ⁻¹				
1	Brandt	40 N, 30 S, 30 Mn, 30 Zn, 2.5 B	2.3	116 N, 87 S, 87 Mn, 87 Zn, 7 B	HCA §	2-July	V10	3
2	Brandt	40 N, 30 S, 30 Mn, 30 Zn, 2.5 B	2.3	116 N, 87 S, 87 Mn, 87 Zn, 7 B	HCA	2-July	V12	3
3	Brandt	40 N, 30 S, 30 Mn, 30 Zn, 2.5 B	2.3	116 N, 87 S, 87 Mn, 87 Zn, 7 B	HCA	2-July	V12	3
4	MAX-IN UZMB	36 S, 10 B, 30 Mn, 40 Zn	2.3	107 S, 89 Mn, 119 Zn, 3 B	HCA	18-June	V6	4
5	MAX-IN B	80 B	2.3	235 B	HCA	17-June	V6	6
6	MAX-IN ZMB	36 S, 10 B, 30 Mn, 40 Zn	2.3	107 S, 89 Mn, 119 Zn, 3 B	HCA	18-June	V5	6
7	MAX-IN Boron	80 B	1.2	123 B	HCA	13-June	V5	6
8	MAX-IN ZMB + MAX-IN	36 S, 10 B, 30 Mn, 40 Zn + 80 B	2.3	107 S, 89 Mn, 119 Zn, 3 B + 235 B	HCA	26-June	V8	4
9	FullTec Zn	300 P ₂ O ₅ , 80 Mn, 30 Zn	0.4	206 P ₂ O ₅ , 55 Mn, 21 Zn	HCA	12-June	V5	4
10	Attain + MAX-IN B	80 N, 30 S, 20 Mn, 30 Zn, 10 Fe + 80 B	2.3	238 N, 89 S, 56 Mn, 89 Zn, 30 Fe	HCA	26-June	V8	8
11	Attain + MAX-IN B	80 N, 30 S, 20 Mn, 30 Zn, 10 Fe + 80 B	2.3	238 N, 89 S, 56 Mn, 89 Zn, 30 Fe	HCA	26-June	V9	8
12	MAX-IN ZMB + MAX-IN B	36 S, 10 B, 30 Mn, 40 Zn + 80 B	2.3	107 S, 89 Mn, 119 Zn, 3 B + 235 B	HCA	3-July	V11	20
13	MAX-IN ZMB + MAX-IN B	36 S, 10 B, 30 Mn, 40 Zn + 80 B	2.3	107 S, 89 Mn, 119 Zn, 3 B + 235 B	HCA	3-July	V11	20
14	MAX-IN ZMB	36 S, 10 B, 30 Mn, 40 Zn	2.3	107 S, 89 Mn, 119 Zn, 3 B	Aerial	10-July	V13	4
15	MAX-IN ZMB	36 S, 10 B, 30 Mn, 40 Zn	2.3	107 S, 89 Mn, 119 Zn, 3 B	Aerial	10-July	V14	4
16	MAX-IN ZMB	36 S, 10 B, 30 Mn, 40 Zn	4.7	218 S, 182 Mn, 242 Zn, 6 B	Aerial	10-July	V13	4
17	MAX-IN ZMB	36 S, 10 B, 30 Mn, 40 Zn	2.3	107 S, 89 Mn, 119 Zn, 3 B	Aerial	10-July	V13	2
18	MAX-IN ZMB + MAX-IN B	36 S, 10 B, 30 Mn, 40 Zn + 80 B	2.3	107 S, 89 Mn, 119 Zn, 3 B + 235 B	HCA	3-July	V11	10
19	Attain + N-Cline	80 N, 30 S, 30 Zn, 20 Mn, 10 Fe + 280 N	2.3 and 9.4	238 N, 89 S, 56 Mn, 89 Zn, 30 Fe + 3343 N	HCA	23-June	V7	6
20	Versa Fe + LS	180 Fe-EDDHA	5.8 L ha ⁻¹ and 0.3 kg ha ⁻¹	123 Fe	Aerial	26-June	V6	4
21	Versa Fe + LS	180 Fe-EDDHA	5.8 L ha ⁻¹ and 0.3 kg ha ⁻¹	123 Fe	Aerial	26-June	V6	4
22	Versa Fe + LS	180 Fe-EDDHA	5.8 L ha ⁻¹ and 0.3 kg ha ⁻¹	123 Fe	Aerial	26-June	V6	4
23	Versa Fe + LS	180 Fe-EDDHA	5.8 L ha ⁻¹ and 0.3 kg ha ⁻¹	123 Fe	Aerial	26-June	V6	4
24	Pro Iron 5	60 N, 30 S, 50 Fe-EDTA	2.3	175 N, 88 S 146 Fe	HCA	25-June	V6	6
25	Versa Fe + LS	180 Fe-EDDHA	5.8 L ha ⁻¹ and 0.3 kg ha ⁻¹	123 Fe	Aerial	26-June	V6	4
26	Versa Fe + LS	180 Fe-EDDHA	5.8 L ha ⁻¹ and 0.3 kg ha ⁻¹	123 Fe	Aerial	26-June	V6	4

† Brandt-Brandt Smart Trio (Zn, Mn, B); ZMB- Zn, Mn and B; LS-Lockdown Surfactant. ‡ AM-Application Method; AD-Application Date; AS-Application Stage. § HCA-High Clearance Applicator.

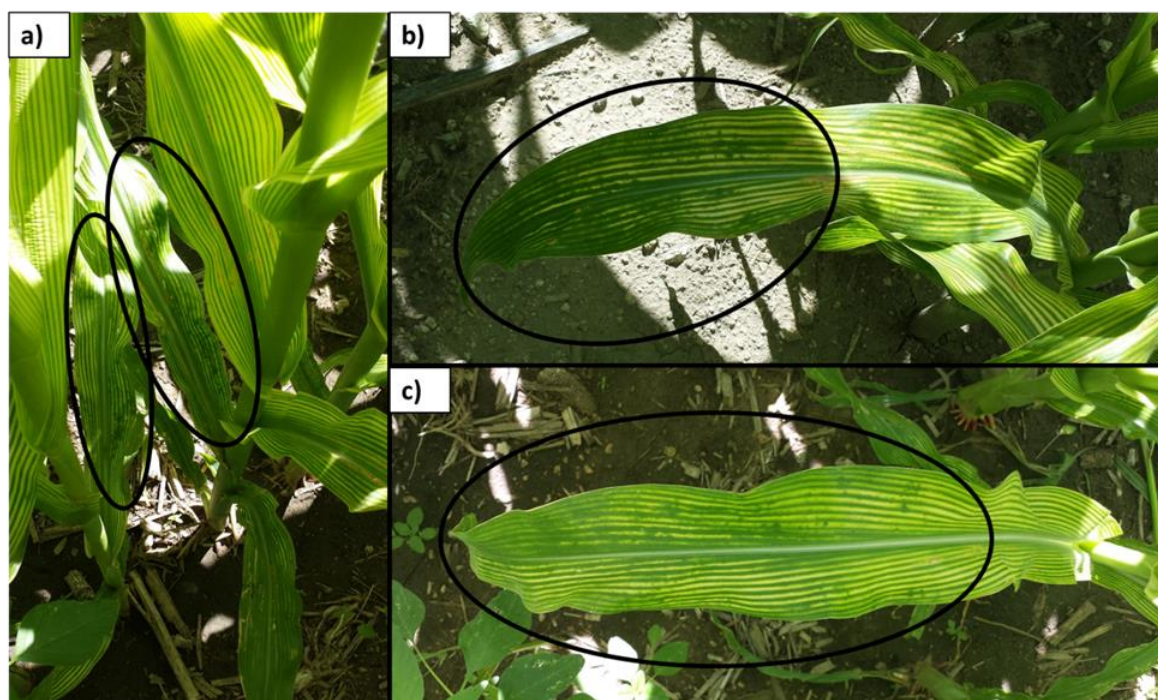


Figure 2. Images from foliar Fe treated maize plants showing regreening patterns where foliar Fe droplets contacted the leaf surface on the V5 leaf (b,c). No regreening appears in upper untreated leaves (a).

Products ranged in micronutrient application rate, method and time, adjuvant formulation, and crop growth stage (Table 2). Management practices varied according to the producers' preferences (Table 1) and soil properties (Table 3). Applications were applied aerially or with a high-clearance applicator in strips with and without the foliar applications and split into adjacent pairs for analysis. Strips ranged in size from approximately 27 to 34 m wide \times 715 m long. The high-clearance applicator did not pass through control strips.

2.3. Sampling and Laboratory Analyses

Plant tissue samples were collected once after application and were composed of 10 unsprayed upper most fully collared leaves [21] and a soil sample of 0–20 cm depth was collected and composed of 14 cores per strip. Grain yield was determined for each strip from 10 m² strip⁻¹ by hand harvest or with a weigh wagon or yield monitor for one combine pass. Grain weight was adjusted to 155 g kg⁻¹ water content. Corresponding plant tissue, soil samples, and grain yield were all collected from the same strip.

Laboratory analysis of plant tissue P, K, S, Fe, Mn, Zn, and B were completed using microwave nitric acid digestion and concentrations determined using inductively-coupled plasma emission spectroscopy (ICP-ES) [22]. Tissue N concentration was determined using the Dumas Method with a Leco FP-428, St. Joseph, MI, USA [23]. Soil samples were dried at 40 °C and ground to pass through a 2-mm sieve prior to analysis. Extractions were with DPTA (diethylenetriaminepentaacetic acid) for B, Mn, and Zn and were extracted with 0.1 N HCl for Fe and Cu and measured with ICAP detection [24] or with sorbitol ICAP detection for B.

Table 3. Soil properties for the 0–20 cm depth at study sites for determining the effects of foliar micronutrient application on maize. No soil micronutrient availability level was below the critical level for deficiency ¶.

Site	Soil Analysis (0–20 cm)															
	Texture †	SOM ‡	CEC §	pH	NO ₃ -N	P Bray 1	P Bray 2	K	Mg	S	Ca	Mn ¶	B ¶	Zn ¶	Fe ¶	Cu
		g kg ⁻¹	meq./100 g	-log(H ⁺)	kg ha ⁻¹							(mg kg ⁻¹)				
1	siL	23.9	18.7	5.6	7.6	7.1	12.3	285	374	10.4	2102	15.3	0.4	2.4	66.6	1.0
2	siL	23.2	17.8	6.2	6.6	20.8	33.0	304	407	11.9	2364	9.5	0.5	1.1	63.3	1.1
3	siL	26.6	18.7	6.0	6.3	5.7	13.0	344	476	9.6	2177	11.0	0.5	1.0	64.2	1.3
4	siL	28.7	26.0	7.1	27.6	29.4	70.5	302	601	10.6	3821	8.3	0.9	3.6	26.6	0.8
5	siCL	26.1	23.9	6.2	17.7	68.3	95.4	354	558	11.9	3015	23.2	0.8	5.9	71.7	1.2
6	siCL	24.2	19.7	6.4	11.9	14.3	23.3	266	468	10.6	2662	11.8	0.7	1.9	51.7	1.5
7	siC	29.8	32.2	6.5	48.9	35.2	107.3	273	793	18.3	4402	15.1	0.8	1.9	53.5	2.8
8	IS	26.0	12.6	6.3	17.9	28.0	53.0	301	206	15.0	1765	7.0	0.4	2.1	37.0	0.9
9	saL and lfs	14.0	12.1	7.6	12.3	74.0	175.0	220	151	13.0	2063	3.0	0.6	5.2	20.0	0.9
10	siL	22.0	22.4	5.6	87.4	68.0	136.0	446	415	17.0	2498	17.0	0.6	1.9	42.0	1.5
11	siL	27.0	20.7	6.0	20.2	110.0	135.0	591	377	14.0	2591	18.0	0.7	3.3	60.0	1.7
12	siCL	21.0	16.1	6.1	9.5	26.0	48.0	224	331	11.0	2116	21.0	0.5	2.1	51.0	1.2
13	siCL	23.0	16.2	6.0	9.0	24.0	43.0	219	336	12.0	2082	22.0	0.5	1.9	49.0	1.1
14	IS	14.0	5.6	6.2	9.0	18.0	22.0	83	96	10.0	771	6.0	0.3	4.6	21.0	0.6
15	IS	13.0	5.6	6.3	8.1	17.0	21.0	81.0	101	11.0	786	6.0	0.3	4.7	23.0	0.5
16	IS	13.0	5.8	6.1	7.8	19.0	26.0	74	98	10.0	799	5.0	0.3	5.9	25.0	0.5
17	IS	12.0	5.9	6.0	7.9	18.0	24.0	76.0	97.0	10.0	773	6.0	0.4	4.9	22.0	0.6
18	siCL	33.0	24.6	7.9	13.5	26.0	84.0	274	342	13.0	4206	5.0	0.9	2.0	18.0	1.9
19	L	27.4	14.1	7.1	53.1	45.0	99.4	595	301	36.6	1983	6.8	0.9	4.1	14.3	0.4
20	IS	17.0	16.9	7.2	78.5	44.0	140.0	332	148	13.0	2956	2.0	0.6	5.6	13.0	0.6
21	vfSL and IS	18.0	17.7	7.5	94.2	13.0	130.0	390	146	13.0	3087	2.0	0.6	5.9	8.0	0.7
22	vfSL and IS	25.0	21.4	8.0	46.0	39.0	118.0	528	192	15.0	3695	2.0	1.0	5.2	10.0	0.7
23	L	23.0	18.8	7.8	59.4	51.0	144.0	495	175	17.0	3216	2.0	1.0	6.7	10.0	0.6
24	L and siL	17.0	22.5	8.2	78.5	4.0	99.0	612	236	26.0	3799	3.0	0.9	3.3	4.0	0.4
25	IS and fS	18.0	13.9	6.3	38.1	66.0	120.0	502	241	14.0	1815	6.0	0.5	2.8	26.0	1.2
26	IS and saL	10.0	7.8	6.1	22.4	43.0	52.0	210	170	10.0	957	6.0	0.4	2.7	48.0	1.3

† Soil texture classes: silt loam (siL), silty clay loam (siCL), silty clay (siC), loamy sand (IS), sandy loam (saL), loamy fine sand (lfs), loam (L), very fine sandy loam (vfSL), and fine sand (fS).

‡ SOM = soil organic matter. § CEC = cation exchange capacity. ¶ Soil critical levels for B, Mn, Fe, and Zn: 0.1, 0.5, 1.0, 0.25 mg kg⁻¹, respectively.

2.4. Statistical Design and Analysis

The experimental design was a paired comparison strip trial (26 paired comparisons). This design was chosen to allow maize producers to use conventional practices to apply (i.e., high clearance and aerial applicators) and select their foliar micronutrient applications based on their relationship with their local agronomist, the availability of foliar micronutrient formulations, and their knowledge of which micronutrient formulation best fits their field site's demand. Site data was analyzed separately and data from sites with identical treatments (i.e., fertilizer source) and crop were combined and analyzed across sites and years. Yield and plant tissue nutrient concentration data were analyzed using the ANOVA procedure in Statistix 10.0 Analytical Software (Analytical Software Tallahassee, FL, USA) with the assumption of fixed treatment and site effects. A mean comparison test using Tukey's HSD was used to compare treatment effects. Data were managed using Microsoft Excel (Microsoft Excel 2013, Microsoft Corp. Santa Rosa, CA, USA) and plotted to test correlations of plant tissue and soil properties with grain yield response using the scatterplot and Pearson correlation coefficient (r) function.

3. Results and Discussion

3.1. Field Sites

Soil test values for micronutrients were above published critical levels at all sites [25] (Table 3) though visual signs of Fe deficiency were observed at some locations. The soil B, Fe, Mn, and Zn concentrations (mg kg^{-1}) ranged from 0.3 to 1.0 for B, 4.0 to 71.7 for Fe, 2.0 to 23.2 for Mn, and 1.0 to 6.7 for Zn. Soil organic matter ranged from 10 to 33 g kg^{-1} and pH ranged from 5.6 to 8.2. Sites included clays, loams, and sands (Table 3). Plant tissue micronutrient concentrations were also above published critical levels at all sites according to Bryson et al. (2014). Maize tissue B, Fe, Mn, and Zn concentrations (mg kg^{-1}) ranged from 3.7 to 16 for B, 59 to 213 for Fe, 38 to 109 for Mn, and 18 to 57 for Zn in untreated plots prior to tassel. The only visual signs of deficiency were at sites 20–24. These sites had high soil pH and plant leaves showed interveinal chlorosis (Figure 2) in upper leaves indicating Fe deficiency although soil and foliar Fe analysis did not indicate deficiency.

3.2. Effects of Foliar Micronutrients on Grain Yield

The effect of foliar micronutrient application at sites 1–19 was not significant for leaf micronutrient concentrations and grain yield with grain yield effects ranging from -0.38 to 0.75 Mg ha^{-1} (Table 4). There were no significant yield increases for any micronutrient product when averaged over the three years (Table 5). In conditions with visual signs of deficiency, although above critical plant tissue levels, foliar Fe supplementation was effective at increasing grain yield by an average of 0.4 Mg ha^{-1} (Figure 3). There were several significant ($p < 0.05$) treatment*site interactions of the treatments on grain yield. These interactions were likely due to unique site conditions such as soil parameters or various hybrids varying in their micronutrient responsiveness.

Overall, there was no significant yield difference across all sites receiving micronutrient application. In conditions without confirmed micronutrient deficiency, yield responses were unpredictable (i.e., as based on prior soil and plant nutrient concentrations) with significant yield increases for sites 1, 14, and 23 and significant decreases for sites 10 and 13 (Table 4). These sites had some combination of foliar B, Mn, Zn, and Fe applied. Site 23 received foliar Fe only (Table 1). The soil pH for the responsive sites ranges from 5.6 to 7.8 and likely affected micronutrient availability and the likelihood of response. Overall, maize grain yield was 0.69 Mg ha^{-1} greater when micronutrients were applied though not significant. The average of significant yield decreases was -0.38 Mg ha^{-1} , which was also not significant. The negative responses only occurred with high-clearance application at V8 and V11 and not by aerial application, which contributed to the uncontrolled variability related to on-farm field trials. This suggests that the yield reduction may be associated with damage incurred during treatment application, as the high-clearance applicator did not pass through the control strips. Additionally, none of the applied micronutrients from the blends led to toxic levels in plant tissue.

Table 4. Maize yield and leaf tissue nutrient concentration without foliar micronutrient application and the response to application.

Site	Yield			Plant Tissue Concentration											
	Trt	Control	Statistic	N	Control N	Statistic	P	Control P	Statistic	K	Control K	Statistic	S	Control S	Statistic
	Mg ha ⁻¹		P > F	g kg ⁻¹		P > F		g kg ⁻¹		P > F	g kg ⁻¹		P > F	g kg ⁻¹	
1	16.19 +†	15.44+	0.06	31.0	30.4	0.27 §	3.0	2.8	0.12	22.8	22.8	1.00	1.8	1.8	0.59 §
2	15.75	15.13	0.40	31.2	30.3	0.61 §	3.1+	2.9+	0.07	24.7	25.3	0.67	2.0	2.1	0.21 §
3	14.62	14.06	0.56	31.0	29.1	0.22 §	2.9	2.7	0.27	22.6	23.6	0.21	1.7	1.7	0.68 §
4	15.57	15.69	0.87	35.1	34.8	0.81	3.7+	3.6+	0.09	20.5	21.0	0.43	1.9	1.9	0.73 §
5	15.94	16.38	0.42	32.5	33.7	0.46	4.3*	4.6*	0.03	19.3	20.7	0.19	2.3	2.1	0.19
6	15.25	15.19	0.20	28.2	30.2	0.41	3.7+	4.4+	0.08	22.4	21.9	0.30	2.7	2.6	0.13 §
7	15.44	15.44	0.98	32.5	34.2	0.13	3.6	3.6	0.92	24.6	23.1	0.30	2.5	2.5	0.35
8	12.74	12.80	0.72	28.6	27.3	0.17	3.4	3.4	0.94	25.3	25.8	0.60	1.6	1.7	0.32 §
9	16.19	16.19	0.69	33.7	33.4	0.28	2.9	2.7	0.50§	22.1	22.7	0.54	1.9	1.9	0.64
10	14.62+	15.19+	0.06	28.5	28.4	0.23 §	2.8	2.8	1.00	29.4	29.3	0.92	2.2 ***	2.3 ***	0.001 §
11	15.13	15.06	0.69	29.7	29.5	0.93 §	3.1	3.0	0.43	30.0	30.0	0.89	2.3	2.3	0.81 §
12	15.69	15.63	0.52	24.5	24.9	0.58	2.3	2.3	0.65	22.3	21.0	0.15	1.8	1.8	0.17 §
13	15.38 ***	15.57 ***	0.001	25.9	26.1	0.71	2.6	2.7	0.43	22.3	22.7	0.28	1.9	1.9	0.62 §
14	13.37 **	12.68 **	0.01	20.0	22.0	0.48	2.3	2.6	0.13	19	21.0	0.54	1.6	1.6	0.52 §
15	13.62	13.37	0.62	22.5	22.7	0.67	3.1	3.0	0.59	20.9	20.9	0.73	1.9	1.8	0.33 §
16	12.49	12.68	0.71	26.3 *	23.5*	0.05	3.2	3.1	0.83	15.9	14.7	0.13	2.1	1.8	0.13 §
17	11.42	11.80	0.58	31.9	30.9	0.34	3.2	3.4	0.35	23.9	24.2	0.42	2.1	2.1	0.47 §
18	13.06	12.68	0.36	31.2	30.4	0.25	3.7	3.7	0.83	25.8	26.2	0.83	1.9	1.9	0.79 §
19	14.25	13.68	0.12	31.4	29.7	0.21§	3.1+	2.9+	0.08	26.8	26.3	0.74	1.8	1.9	0.84 §
20	12.30	11.99	0.49	34.5	32.7	0.27	3.9	3.6	0.17	30.5*	26.3*	0.04	2.3	2.2	0.44
21	13.18	13.06	0.59	33.1	31.1	0.25	4.0	3.9	0.62	32.3	33.3	0.70	2.3	2.2	0.14
22	12.37	13.12	0.13	33.8	31.2	0.27	5.3	4.7	0.13	34.7	34.9	0.91	2.2 +	2.1+	0.06
23	13.87 **	13.24 **	0.01	30.3	31.7	0.35	4.5*	5.0*	0.02	33.3	32.3	0.72	2.0	2.1	0.41
24	10.92	11.30	0.70	32.7	32.7	0.29§	3.9	3.6	0.41	31.2	29.4	0.81	2.9	3.0	0.36
25	4.90	4.90	0.97	32.0	31.5	0.84	3.9*	3.6*	0.05	36.2	34.5	0.46	2.1	2.0	0.39
26	7.59	7.47	0.28	37.5	38.1	0.71	4.2	4.4	0.44	29.8	28.9	0.46	2.6	2.8	0.25

Site	Yield			Plant Tissue Concentration											
	Trt	Control	Statistic	Zn	Control Zn	Statistic	Mn	Control Mn	Statistic	B	Control B	Statistic	Fe	Control Fe	Statistic
	Mg ha ⁻¹		P > F	g kg ⁻¹		P > F		g kg ⁻¹		P > F	g kg ⁻¹		P > F	g kg ⁻¹	
1	16.19 +†	15.44 +	0.06	32	30	0.32 §	87 ***	75 ***	0.001 §	6.3	5.0	0.27 §	189	181	0.47
2	15.75	15.13	0.40	35 *	31 *	0.03 §	80	71	0.41 §	5.0	5.0	1.00 §	124	122	0.75
3	14.62	14.06	0.56	31	27	0.16 §	84	77	0.58 §	7.0	6.3	0.53 §	158	153	0.63
4	15.57	15.69	0.87	34	33	0.25 §	73 *	57*	0.05 §	5.5	5.0	0.18 §	197	213	0.14
5	15.94	16.38	0.42	20	21	0.87	80	98	0.32	5.5	5.8	0.53 §	137	136	0.91
6	15.25	15.19	0.20	23 +	22 +	0.06 §	46 *	57*	0.03 §	4.2	3.7	0.58 §	138	140	0.87

Table 4. Cont.

Site	Yield			Plant Tissue Concentration											
	Trt	Control	Statistic	Zn	Control Zn	Statistic	Mn	Control Mn	Statistic	B	Control B	Statistic	Fe	Control Fe	Statistic
	Mg ha ⁻¹		P > F	g kg ⁻¹		P > F	g kg ⁻¹		P > F	g kg ⁻¹		P > F	g kg ⁻¹		P > F
7	15.44	15.44	0.98	29	27	0.13	67	64	0.76	5.0	8.0	0.16 §	176	171	0.19
8	12.74	12.80	0.72	23	18	0.10 §	54	59	0.28 §	6.5	7.8	0.19 §	118	124	0.27
9	16.19	16.19	0.69	17	18	0.24 §	50 *	62*	0.05 §	6.4	6.7	0.15	103	107	0.22
10	14.62 +	15.19 +	0.06	27 *	23*	0.02 §	96 *	109 *	0.05 §	8.5+	9.3+	0.08	128 *	141 *	0.04 §
11	15.13	15.06	0.69	22	19	0.23 §	67	78	0.51 §	9.2	9.7	0.66	125	122	0.84 §
12	15.69	15.63	0.52	23 **	18**	0.0003 §	90	82	0.36 §	4.9	4.6	0.71 §	131	134	0.32
13	15.38 ***	15.57 ***	0.001	19	18	0.24 §	48	41	0.31 §	4.7	4.3	0.43 §	164	161	0.83
14	13.37 **	12.68 **	0.01	26 *	19*	0.05 §	59	38	0.20 §	5.5	6.5	0.70 §	117	112	0.25
15	13.62	13.37	0.62	29	20	0.13 §	57	63	0.74 §	6.4	6.1	0.61 §	113	109	0.64
16	12.49	12.68	0.71	41 +	26+	0.06 §	48	58	0.63 §	5.5	6.5	0.70 §	152	146	0.45
17	11.42	11.80	0.58	31 *	22*	0.03 §	59	54	0.84 §	6.2	5.9	0.48 §	150	146	0.33
18	13.06	12.68	0.36	18	18	0.74 §	68	67	0.82 §	5.5	6.0	0.71 §	163	154	0.32
19	14.25	13.68	0.12	21	21	0.87 §	69*	60*	0.05 §	7.0	6.0	0.50	79	72	0.18 §
20	12.30	11.99	0.49	33	27	0.13	66	48	0.35	17.0	16.0	0.96	86	80	0.73 §
21	13.18	13.06	0.59	30	30	0.87	57	58	0.59	16.0	12.0	0.36	72	69	0.48 §
22	12.37	13.12	0.13	41	42	0.91	71	72	0.90	12.0	11.0	0.52	68+	59+	0.10 §
23	13.87 **	13.24 **	0.01	40	43	0.54	67	69	0.75	11.0	12.0	0.60	70	60	0.19 §
24	10.92	11.30	0.70	54	57	0.19	98	97	0.41	11.0	12.0	0.72	68	72	0.27 §
25	4.90	4.90	0.97	32	30	0.46	48	51	0.51	8.0	8.0	1.00	94	92	0.73 §
26	7.59	7.47	0.28	45	47	0.42	67	71	0.40	21.0	21.0	0.87	116	124	0.33 §

† Means followed by mean comparison significant F test: Not Significant > 0.10; + >0.05; * >0.01; ** >0.001; *** <0.001. § Plant parameter received a foliar application of the corresponding analyzed elemental concentration.

Table 5. The mean response across ≥ 2 sites for identical foliar micronutrient application compared to no application on grain yield and leaf tissue nutrient concentrations.

Product †	Sites	Total Repts	Yield			N			P		
			Trt ‡	Site §	Trt*Site §	Trt	Site	Trt*Site	Trt	Site	Trt*Site
			Mg ha ⁻¹	P > F	P > F	g kg ⁻¹	P > F	P > F	g kg ⁻¹	P > F	P > F
Brandt	1, 2, 3	9	0.7 +¶	0.03 *	0.97	0.13 *#	0.59 #	0.62 #	0.2 **	0.13	0.68
MAX-IN B	5, 7	12	-0.2	0.06 +	0.56	-1.5 +	0.77	0.74	-0.1	<0.001 ***	0.13
MAX-IN ZMB	4, 6, 14, 15, 16, 17	25	0.1	<0.001 ***	0.63	-0.1	<0.001 ***	0.29	-0.2	<0.001 ***	0.17
MAX-IN ZMB + MAX-IN B	8, 12, 13, 18	54	0.1	<0.001 ***	0.17	0.60	<0.001 ***	0.22	0.010	<0.001 ***	0.94
Attain (Zn, Mn, Fe, B) + MAX-IN B	10, 11	16	-0.3	0.35	0.05 *	-0.4 #	0.08 +#	0.55#	0.07	0.10 +	0.38
Versa Fe + LS (corn)	20, 21, 22, 23	16	0.4**	0.04 *	0.03 *	1.20	0.44	0.28	0.20	<0.001 ***	0.02 *
Versa Fe + LS (popcorn)	25, 26	8	0.1	<0.001 ***	0.56	-0.06	0.002 **	0.63	0.06	0.02 *	0.07 +
Product †	Sites	Total Repts	K			S			Zn		
			Trt	Site	Trt*Site	Tr	Site	Trt*Site	Trt	Site	Trt*Site
			g kg ⁻¹	P > F	P > F	g kg ⁻¹	P > F	P > F	mg kg ⁻¹	P > F	P > F
Brandt	1, 2, 3	9	-0.5	0.01 **	0.68	-0.03 #	0.03 *#	0.24 #	3.4 ***#	0.34 #	0.45
MAX-IN B	5, 7	12	0.04	0.004 **	0.10+	0.10	0.14	0.43	1.2	<0.001 ***#	0.14
MAX-IN ZMB	4, 6, 14, 15, 16, 17	25	-0.2	<0.001 ***	0.26	0.02 #	0.006 ***#	0.01 *#	6.1 ***#	<0.001 ***#	<0.001 ***#
MAX-IN ZMB + MAX-IN B	8, 12, 13, 18	54	0.10	<0.001 ***	0.45	-0.003 #	0.02 *#	0.48 #	3.3 ***#	0.30 #	0.01 ***#
Attain (Zn, Mn, Fe, B) + MAX-IN B	10, 11	16	-0.02	0.45	0.87	-0.07 #	0.36 #	0.58 #	2.9 ***#	0.009 **#	0.68 #
Versa Fe + LS (corn)	20, 21, 22, 23	16	1.00	0.02 *	0.33	0.040	0.21	0.22	0.8	0.007 **	0.50
Versa Fe + LS (popcorn)	25, 26	8	1.30	<0.001 ***	0.72	-0.04	<0.0001 ***	0.11	0.3	0.02 *	0.26
Product †	Sites	Total Repts	MN			B			Fe		
			Trt	Site	Trt*Site	Trt	Site	Trt*Site	Trt	Site	Trt*Site
			mg kg ⁻¹	P > F	P > F	mg kg ⁻¹	P > F	P > F	mg kg ⁻¹	P > F	P > F
Brandt	1, 2, 3	9	9.3 *#	0.44 #	0.91 #	0.7 #	0.05 *#	0.47#	5.0	0.17	0.25
MAX-IN B	5, 7	12	-7.2	0.03 *	0.28	-1.7 +#	0.35 #	0.15#	3.0	0.09 +	0.16
MAX-IN ZMB	4, 6, 14, 15, 16, 17	25	4.2 +#	0.10 +#	0.005 **#	-0.3 #	0.004 ***#	0.34#	-2.0	0.34	0.13
MAX-IN ZMB + MAX-IN B	8, 12, 13, 18	54	1.7 #	0.04 *#	0.53 #	-0.5 #	0.01 **#	0.53#	-2.3	0.01 **	0.33
Attain (Zn, Mn, Fe, B) + MAX-IN B	10, 11	16	-1.5 #	0.01 ***#	0.91 #	-0.6 #	0.60 #	0.81#	-5.0 #	0.10 +#	0.22 #
Versa Fe + LS (corn)	20, 21, 22, 23	16	3.4	0.06 +	0.35	1.1	0.29	0.91	8.1 +#	0.04 *#	0.91 #
Versa Fe + LS (popcorn)	25, 26	8	-3.8	0.02 *	0.88	0.1	<0.001 ***	0.89	-3.6 #	0.005 **#	0.27 #

† Brandt- Brandt Smart Trio (Zn, Mn, B); ZMB-Zn, Mn and B; LS-Lockdown Surfactant. ‡ Mean difference between control and treatment. Negative values indicate the control is greater than the treatment mean. § P statistic for site effect and trt*site interactions. ¶ Significant F test: Not Significant > 0.10; + > 0.05; * > 0.01; ** > 0.001; *** < 0.001. # Plant parameter received a foliar application of the corresponding analyzed elemental concentration.

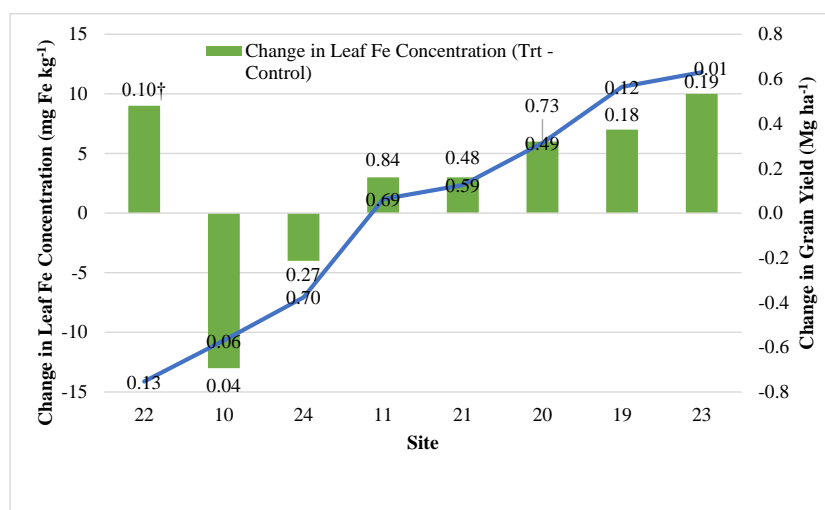


Figure 3. Leaf Fe concentration (bars) and maize grain yield (line) responses to foliar Fe application for eight sites. Data labels on both the line and bar graphs indicate p -values † for mean comparison differences. The correlation coefficient (r) for the relationship of changes in tissue Fe concentration and grain yield due to foliar Fe application is 0.54. These sites were the only sites with visual signs of micronutrient deficiency.

Inversely, the combined analysis of variance for identical treatments at four different sites in 2015 indicates that an aerial foliar application of 123 g Fe ha⁻¹ increased grain yield ($p = 0.04$) by an average of 0.4 Mg ha⁻¹ with soil pH of 7.2 to 8.0, soil test Fe of 8.0 to 13.0 mg kg⁻¹, tissue Fe concentration prior to tassel of 68 to 86 mg kg⁻¹, and visual signs of Fe deficiency (Figure 2) (Table 5). Additionally, visual observations of treated strips showed small regreening patterns where foliar Fe droplets contacted the leaf surface on the V5–6 leaf (Figure 2). No regreening appeared in upper untreated leaves (Figure 2a). Iron and most micronutrients are considered relatively immobile within plant tissue (Bryson et al., 2014). Thus, no regreening in upper untreated new growth leaves was expected nor observed, confirming previously described deficiency correction theory [20]. However, plant and soil Fe concentrations alone were not predictive indicators of grain yield response to foliar Fe. This is consistent with the findings from a hydroponics study evaluating foliar Fe [26]. Micronutrient supplementation must be both predictable for grain yield response and lead to an increase that is great enough to cover the added cost, which is not evident in these trials. It is of note that the lack of significant yield differences may also be due to high levels of variability as in the case of on-farm field trials (i.e., type II error).

3.3. Effects of Foliar Micronutrients on Leaf Tissue Concentrations

Foliar micronutrient applications were more consistent in increasing their respective micronutrient concentrations in leaf tissue than in increasing grain yield, especially in the case of Zn (Figures 3–6) (Table 4). Of the sites that received foliar Zn, 47% had a nearly significant increase ($p < 0.10$) of an average of 4 mg Zn kg⁻¹ in the leaf tissue (Figure 4) (Table 5) which is consistent with other results from a hydroponic greenhouse study (Stewart et al., 2019). In general, the primary nexus for deciding to apply Zn was high, yielding maize locations aiming to boost yields with low plant or soil Zn concentrations but otherwise not below critical levels. Foliar application also affected plant N and P concentrations. The combined analysis of sites 1, 2, and 3 which received 116, 87, 87, 87, and 7 g of N, S, Mn, Zn, and B ha⁻¹, respectively, increased plant N by 1.3 g kg⁻¹ and plant P by 0.2 g kg⁻¹ ($p < 0.05$) (Table 5). The increase in N would be expected with the addition of foliar N, and sulphur application also has synergistic impact on N uptake in plant [27]. The increase in P may have been due to the interaction of P with Fe, Mn, or Zn [28].

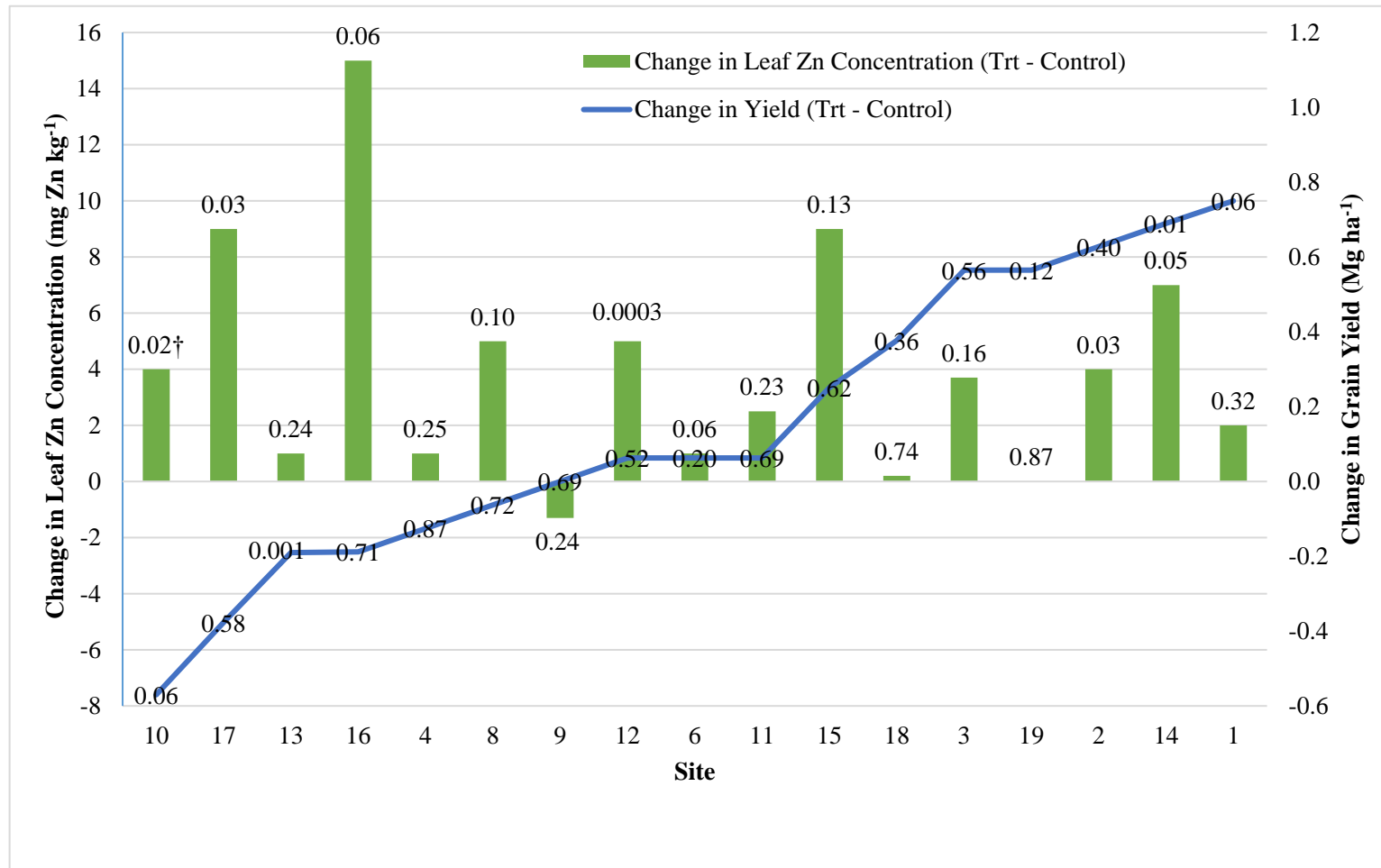


Figure 4. Leaf Zn concentration (bars) and maize grain yield (line) responses to foliar Zn application for 17 sites. Data labels on both the line and bar graphs indicate *p*-values † for mean comparison differences. The correlation coefficient (*r*) for the relationship of changes in tissue Zn concentration and grain yield due to foliar Zn application is 0.2.

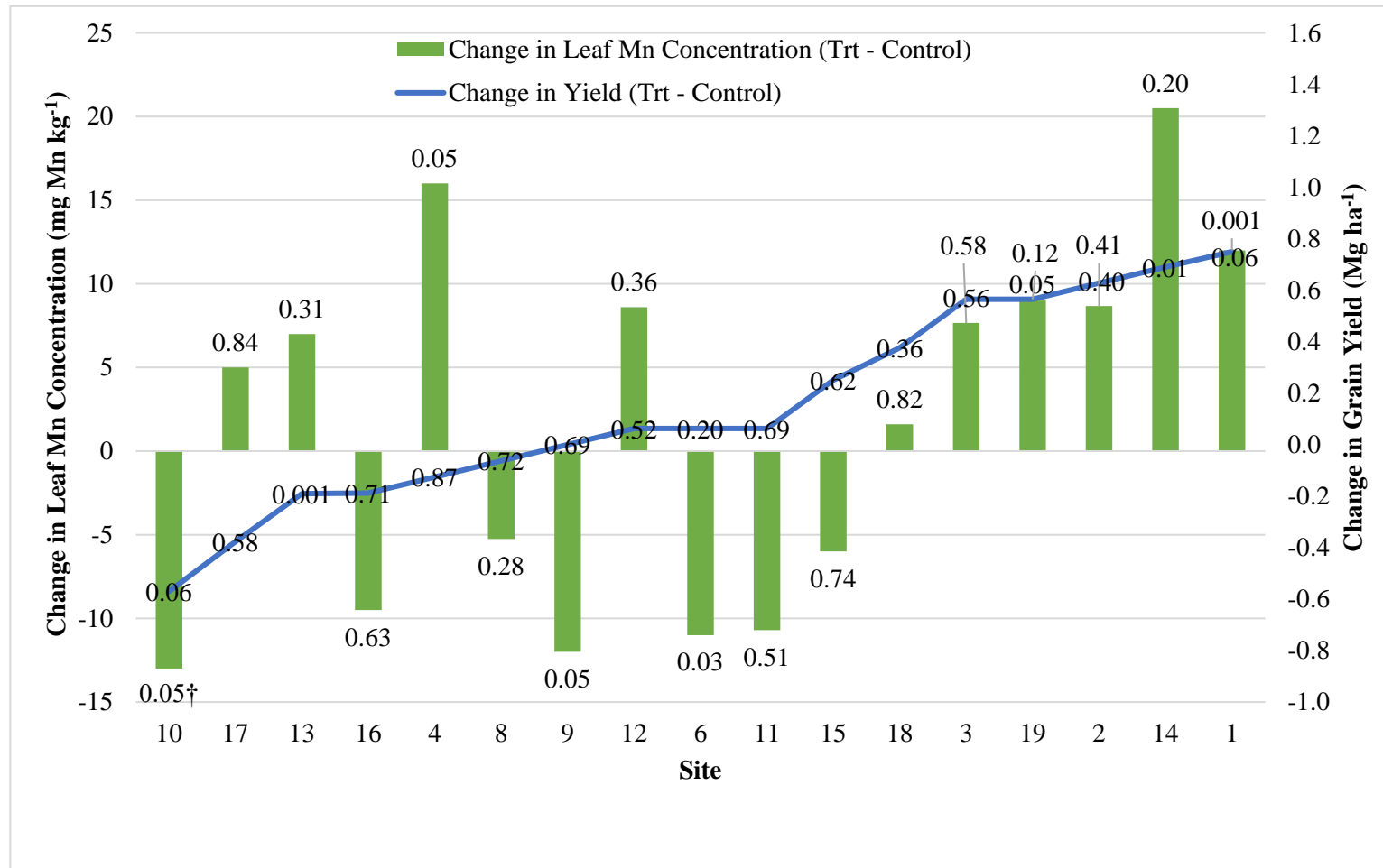


Figure 5. Leaf Mn concentration (bars) and maize grain yield (line) responses to foliar Mn application for 17 sites. Data labels on both the line and bar graphs indicate *p*-values † for mean comparison differences. The correlation coefficient (*r*) for the relationship of changes in tissue Mn concentration and grain yield due to foliar Mn application is 0.54.

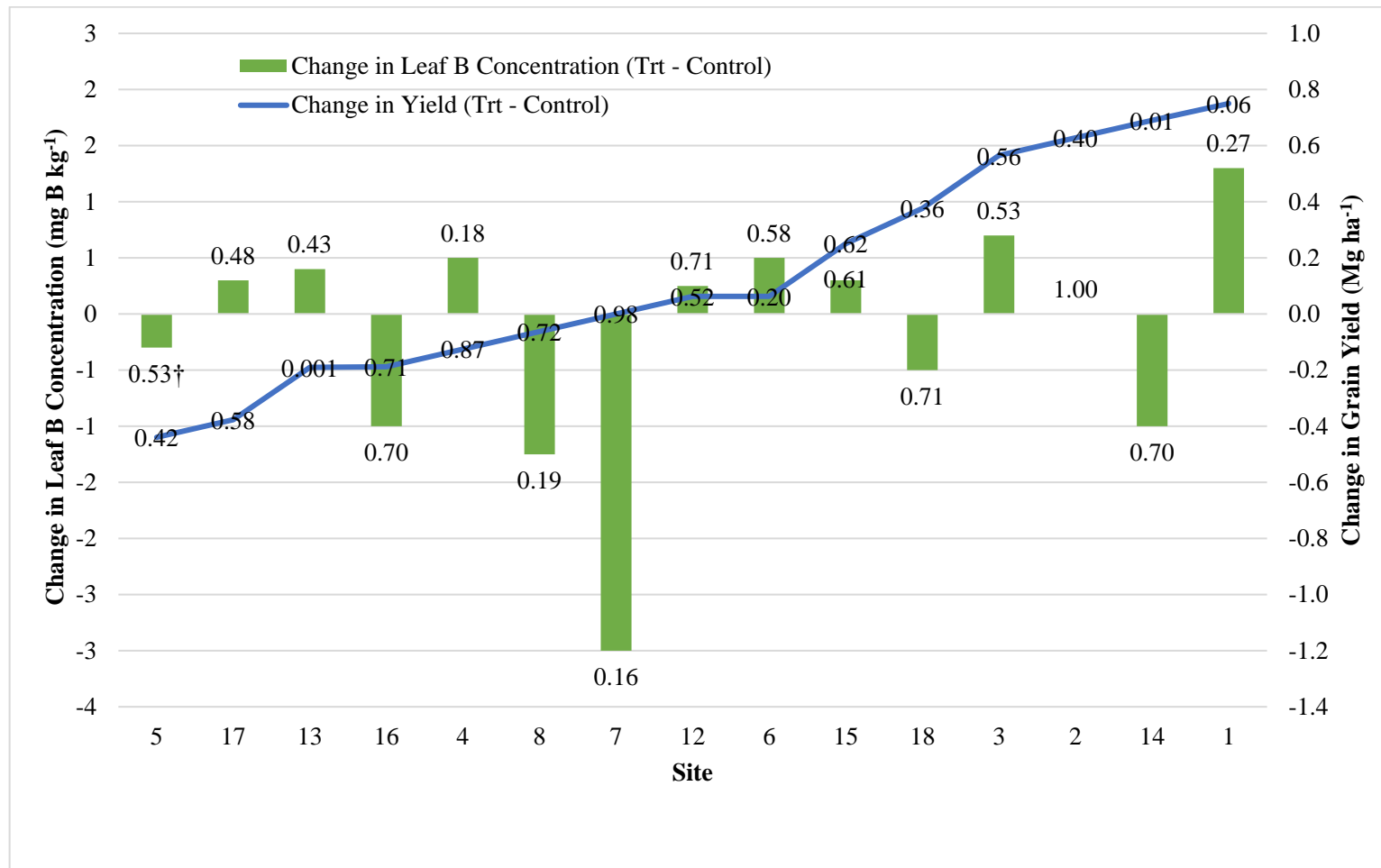


Figure 6. Leaf B concentration (bars) and maize grain yield (line) responses to foliar B application for 15 sites. Data labels on both the line and bar graphs indicate *p*-values † for mean comparison differences. The correlation coefficient (*r*) for the relationship of changes in tissue B concentration and grain yield due to foliar B application is 0.2.

For the combined year and site analysis, foliar applications of 87 to 119 g Zn ha⁻¹ at 17 sites, regardless of product formulation, significantly increased Zn concentration ($p < 0.05$) in plant tissue by 2.9 to 6.1 mg kg⁻¹; however, these increases were not consistently associated with an increase in grain yield (Table 4). Foliar applications of 87 to 89 g Mn ha⁻¹ at 17 sites also had increased plant tissue Mn concentrations by 9.3 ($p < 0.05$) to 4.2 ($p < 0.10$) mg kg⁻¹, with a positive correlation with increased grain yield $r = 0.54$ but without a significant three-year average yield increase in any product formulation (Figure 5; Table 5). One site (i.e., site 10) had a significant decrease in Mn and Fe due to their application from 109 to 96 g Mn ha⁻¹ and 141 to 128 g Fe ha⁻¹, which corresponded with a decrease in grain yield by 0.57 kg ha⁻¹ ($p = 0.06$). Foliar applications of B at a rate of 3 to 235 g B ha⁻¹ did not affect plant tissue B concentrations nor grain yield at any of the 15 sites receiving foliar B (Table 4; Figure 6). Though there was a direct linkage between the application of a micronutrient blend and the increase in the corresponding nutrient in the plant tissue, we cannot establish a direct relationship between any singular nutrient and the lack of grain yield response.

Application of 123 g foliar Fe ha⁻¹ at four sites increased plant tissue Fe concentration ($p = 0.1$) with correlated yield increases that averaged 0.4 Mg ha⁻¹ ($p = 0.04$) (Table 5). This response of plant tissue concentrations and grain yield to the foliar Fe application was consistent with the deficiency correction theory in that there were visual signs of Fe deficiency identified at sites 20–23 prior to foliar Fe application and thus, there was an increase in grain yield due to the application of Fe. However, neither the soil nor the plant tissue concentrations were below reported critical values for Fe and thus were not predictive of the associated increase in grain yield. This may also suggest that the critical levels for plant tissue and soil Fe may need to be updated and that precision agriculture technologies may be valuable to match deficiency symptoms with application [29]. Additionally, sites receiving foliar B, Mn, and Zn applications under conditions with no respective deficiency identified by plant tissue samples, soil samples, or visual symptoms, did not have a yield increase for a three-year average.

3.4. Relationship between Higher Grain Yield and Response to Foliar Micronutrients

Due to increased micronutrient demand of higher yielding sites, we hypothesized that sites with higher yields and lower micronutrient plant or soil concentrations but not necessarily below critical levels, may be more likely to have increased yield response due to foliar micronutrient supplementation. The combined analysis for maize production sites showed no relationship ($r = 0.03$) between yield level and yield response to foliar micronutrient supplementation (Figure 7). Additionally, sites with micronutrient concentrations in soil or plant tissue near critical levels but not below were not consistently associated with an increased likelihood of increased grain yield ($r < 0.1$). Neither soil organic matter, pH, nor soil/plant P was correlated ($r < 0.01$) with a positive increase in grain yield.

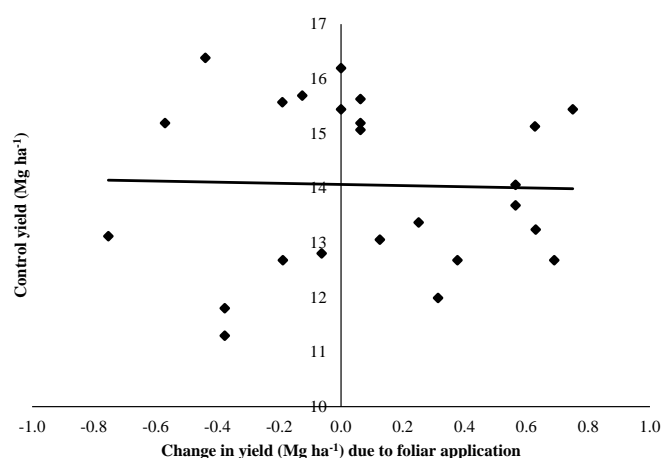


Figure 7. Relationship between the control maize grain yield and the grain yield response to foliar micronutrient application for 26 sites. Our hypothesis was that higher yielding sites would have a greater yield response but this relationship did not occur ($r = 0.03$).

4. Conclusions

The objective of these on-farm strip-trials was to evaluate the effect of foliar-applied micronutrients on grain yield and plant tissue nutrient status under current management practices using commercially available foliar micronutrients. This research was conducted across a wide range of irrigated maize production conditions, and the results are widely applicable to high yield maize production with similar soil and plant micronutrient status. These data are largely supportive of the deficiency correction theory and refute the use of foliar micronutrient applications for high-yield situations. Higher yielding locations were not associated with an increased likelihood of response to foliar micronutrients, thus rejecting the first hypothesis.

Soil test results and plant tissue nutrient concentrations were found to not be predictive of yield response under high-yielding conditions. However, no sites reported soil or plant tissue micronutrient concentrations below critical levels [20]. Nonetheless, there were some significant yield increases indicating a need for better means of predicting yield response to foliar micronutrient application if such treatments are to be profitable. These results are not sufficient to revise previously established critical values but do suggest that sites with plant tissue concentration or soil availability for Fe near to critical levels may still be candidates for foliar Fe application, especially if associated deficiency symptoms and calcareous soil. The mean grain yield response to 123 g foliar Fe ha⁻¹ was 0.4 Mg ha⁻¹ for the four sites with Fe deficiency symptoms. Without visual signs of deficiency or other confirmation of a micronutrient deficiency, yield response to foliar applications of micronutrients remains elusive, thus accepting the second hypothesis for visual signs of deficiency being associated with an increased likelihood of response but rejecting the hypothesis for critical levels being associated with an increased likelihood of response.

Though the use of foliar micronutrient blends made it challenging to decipher which nutrient had the causal relationship with changes in grain yield, the causal linkage of the applied micronutrient to changes in leaf tissue concentration were clearer. Micronutrient concentrations for leaf growth that occurred after foliar applications were significantly increased for Zn, Mn, and Fe but not for B. Thus, the third hypothesis is accepted that applied micronutrients will increase their corresponding foliar concentration for Zn, Mn, and Fe and reject for B.

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References

1. Bender, R.R.; Haegele, J.W.; Ruffo, M.L.; Below, F.E. Nutrient uptake, partitioning, and remobilization in modern, transgenic insect-protected maize hybrids. *Agron. J.* **2013**, *105*, 161–170. [[CrossRef](#)]
2. Dobermann, A.; Shapiro, C.A. *Setting a Realistic Corn Yield Goal*; Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln: Lincoln, NE, USA, 2004.

3. van der Ploeg, R.R.; Kirkham, M. On the origin of the theory of mineral nutrition of plants and the law of the minimum. *Soil Sci. Soc. Am. J.* **1999**, *63*, 1055–1062. [[CrossRef](#)]
4. Marschner, P. *Marschner's Mineral Nutrition of Higher Plants*; Academic Press: New York, NY, USA, 2012.
5. Fageria, N.; Filho, M.B.; Moreira, A.; Guimaraes, C. Foliar fertilization of crop plants. *J. Plant Nutr.* **2019**, *32*, 1044–1064. [[CrossRef](#)]
6. Kannan, S. *Foliar Fertilization for Sustainable Crop Production. Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming*; Springer: Amsterdam, The Netherlands, 2010; pp. 371–402.
7. Fernández, V.; Eichert, T. Uptake of hydrophilic solutes through plant leaves: Current state of knowledge and perspectives of foliar fertilization. *Crit. Rev. Plant Sci.* **2009**, *28*, 36–68. [[CrossRef](#)]
8. Stewart, Z.P. Micronutrient Foliar Analysis and Supplementation in Nutrient Management for High Yield Maize (*Zea mays* L.). Doctoral Dissertation, University of Nebraska-Lincoln, Lincoln, NE, USA, 2016.
9. Fernández, V.; Ebert, G. Foliar iron fertilization: A critical review. *J. Plant Nutr.* **2005**, *28*, 2113–2124. [[CrossRef](#)]
10. Wojcik, P. Uptake of mineral nutrients from foliar fertilization. *J. Fruit Ornament. Plant Res.* **2004**, *12*, 201–218.
11. Zhang, Q.; Brown, P.H. The mechanism of foliar zinc absorption in pistachio and walnut. *J. Am. Soc. Hortic. Sci.* **1999**, *24*, 312–317. [[CrossRef](#)]
12. Potarzycki, J.; Grzebisz, W. Effect of zinc foliar application on grain yield of maize and its yielding components. *Plant Soil Environ.* **2009**, *55*, 519–527. [[CrossRef](#)]
13. Heckman, J.R. Foliar applied boron for high yield corn: Research update. *Mid Atl. Grain Forage J.* **2002**, *8*, 24–25.
14. Mueller, N.D.; Diaz, D.A.R. Improving corn and soybean yields with starter and foliar fluid fertilizers. *Proc. 2011 Fluid Forum* **2011**, *28*, 108.
15. Nelson, K.A.; Meinhardt, C. Foliar boron and pyraclostrobin effects on corn yield. *Agron. J.* **2011**, *103*, 1352–1358. [[CrossRef](#)]
16. Mundorf, T.; Wortmann, C.; Shapiro, C.; Paparozzi, E. Time of day effect on foliar nutrient concentrations in corn and soybean. *J. Plant Nutr.* **2015**, *38*, 2312–2325. [[CrossRef](#)]
17. Enderson, J.T.; Mallarino, A.P.; Haq, M.U. Soybean yield response to foliar-applied micronutrients and relationships among soil and tissue tests. *Agron. J.* **2015**, *107*, 2143–2161. [[CrossRef](#)]
18. Maharjan, B.; Shaver, T.M.; Wortmann, C.S.; Shapiro, C.A.; Ferguson, R.B.; Krienke, B.T.; Stewart, Z.P. Micronutrient management in Nebraska. 2018. *Nebraska Extension. NebGuide G1830MR*. Available online: <https://cropwatch.unl.edu/2018/new-nebguide-micronutrient-management-nebraska> (accessed on 24 April 2018).
19. Shapiro, C.A.; Ferguson, R.B.; Hergert, G.W.; Dobermann, A.; Wortmann, C. *Fertilizer Suggestions for Corn*; Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln: Lincoln, NE, USA, 2003.
20. Bryson, G.M.; Mills, H.A.; Sasseville, D.N.; Jones, J.B., Jr.; Barker, A.V. *Plant Analysis Handbook III: A Guide to Sampling, Preparation, Analysis, and Interpretation for Agronomic and Horticultural Crops*; Micro-Macro Publishing Inc.: Athens, GA, USA, 2014.
21. Abendroth, L.; Elmore, R.; Boyer, M.; Marlay, S. *Corn Growth and Development PMR 1009*; Iowa State University Extension: Ames, IA, USA, 2011.
22. Miller, R.O.; Gavlak, R.; Horneck, D. *Soil, Plant and Water Reference Methods for the Western Region (WREP-125)*, 4th ed.; Colorado State University: Fort Collins, CO, USA, 2013.
23. Horwitz, W.; Latimer, G.W., Jr. *Official Methods of Analysis*; Association of Official Analytical Chemists: Washington, DC, USA, 1920.
24. Brown, J.R. *Recommended Chemical Soil Test Procedures for the North Central Region*; Missouri Agricultural Experiment Station, University of Missouri-Columbia: Missouri, DC, USA, 1998.
25. Ward, R.C. *WARDguide, 2015*. Ward Laboratories, Inc. Kearney, Nebraska. Available online: www.wardlab.com (accessed on 1 January 2016).
26. Stewart, Z.P.; Paparozzi, E.T.; Djanaguiraman, M.; Shapiro, C.A. Lipid-based Fe-and Zn-nanoformulation is more effective in alleviating Fe-and Zn-deficiency in maize. *J. Plant Nutr.* **2019**, *42*, 1693–1708. [[CrossRef](#)]
27. Li, N.; Yang, Y.; Wang, L.; Zhou, C.; Jing, J.; Sun, X.; Tian, X. Combined effects of nitrogen and sulfur fertilization on maize growth, physiological traits, N and S uptake, and their diagnosis. *Field Crops Res.* **2019**, *242*, 107593. [[CrossRef](#)]

28. Warnock, R. Micronutrient uptake and mobility within corn plants (*Zea mays* L.) in relation to phosphorus-induced zinc deficiency. *Soil Sci. Soc. Am. J.* **1970**, *34*, 765–769. [[CrossRef](#)]
29. Stewart, Z.P.; Stepanovic, S.; Shapiro, C. Iron management in high pH soils: A strong candidate for precision farming technologies. In Proceedings of the Great Plains Soil Fertility Conference, IPNI, Denver, CO, USA, 1–2 March 2016.

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