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Foliar Application of Iron Fertilizers to Control Iron Deficiency Chlorosis of Soybean

A. Chatterjee,* S. Lovas, H. Rasmussen, and R.J. Goos

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Abstract

Soybean [*Glycine max* (L.) Merr.] production is significantly reduced by iron (Fe) deficiency chlorosis under calcareous soils of the Northern Great Plains. On-farm trials were conducted to evaluate the foliar applications of Fe fertilizer forms and addition of different adjuvants according to regreening of leaves and yield. Treated plots had improved visual chlorosis ratings and chlorophyll soil plant analysis development (SPAD) meter readings over the growing season than control, but differences were not significant ($P < 0.05$). Foliar application of Fe-EDDHA had the most consistent increase in yield over control of the Fe chelates, but no single adjuvant performed better than the others. Future research should focus on integrating other practices like cultivar selection and high seeding rate with foliar application to control Fe deficiency chlorosis.

Iron (Fe) deficiency chlorosis (IDC) is a widespread problem for soybean [*Glycine max* (L.) Merr.] production, particularly under calcareous soils of the north-central region of the United States (Goos and Johnson, 2000). According to USDA-NASS (2016), average soybean production was 34 bu/acre, and IDC could reduce the yield by 32% (~11 bu/acre) in North Dakota (Hansen et al., 2004). Soil factors like alkaline pH, excess moisture, low temperature, elevated bicarbonate and soluble salts, and poor aeration reduce solubility of Fe (Lindsay, 1979; Lucena, 2000; Schenkeveld et al., 2008; Bloom et al., 2011).

Conventional management of IDC involves seed treatment and foliar application of Fe fertilizers, higher seeding rate, and planting Fe-efficient cultivars (Goos and Johnson, 2000; Helms et al., 2010). Soil applied Fe chelates, particularly Fe-ortho-ortho-EDDHA [ethylenediamine-*N*, *N*′-bis(2-hydroxyphenylacetic acid)], may provide some protection against IDC (Goos and Germain, 2001; Wiersma, 2005). However, the success of soil-applied Fe-EDDHA in reaching plant roots can be reduced due to leaching from rhizosphere, adsorption to various soil constituents, and photodegradation (Hernández-Apaolaza and Lucena, 2001; Rombolà and Tagliavini, 2006). Iron chelates include both polymeric and nonpolymeric molecules that are derived from natural origins (e.g., humates, lignosulfonates, amino acids, gluconate, and citrate). These are cheaper but degrade more easily than synthetic chelates, so they are generally recommended for foliar applications (Rodríguez-Lucena et al., 2010).

Core Ideas

- Iron deficiency chlorosis reduces soybean yield in the Northern Great Plains.
- Fe-ortho-ortho-EDDHA performed better than other iron forms.
- Foliar application after iron deficiency chlorosis appearance did not increase yield.

A. Chatterjee, S. Lovas, H. Rasmussen, and R.J. Goos, Dep. of Soil Science, North Dakota State Univ., Fargo, ND 58108. *Corresponding author (amitava.chatterjee@ndus.edu).

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Abbreviations: IDC, iron deficiency chlorosis; SPAD, soil plant analysis development.

Conversions: For unit conversions relevant to this article, see Table A.

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Table A. Useful conversions.

To convert Column 1 to Column 2, multiply by	Column 1 Suggested unit	Column 2 SI unit
0.016	pound per cubic foot, lb/ft^3	gram per cubic centimeter, g/cm^{-3}
2.24	ton per acre, ton/acre	megagram per hectare, Mg/ha
16.02	pound per cubic foot, lb/ft^3	gram per liter, g/L
0.03	milliliter, mL	US fluid ounce, fl oz
0.26	liter, L	US liquid gallon, g
28.35	ounce, oz	gram, g
6.89	pound per square inch, lb/sq inch	kilopascal (kPa)
67.25	bushel /acre, bu/acre	kilogram per hectare, kg/ha
1.121	pound per acre, lb/acre	kilogram per hectare, kg/ha
°C ´ 1.8 + 32	degree Celsius,°C	degree Fahrenheit, °F

Foliar application of Fe chelates with a good surfactant may increase the absorption of Fe through leaf and is more cost effective than soil application (Abadía et al., 2011). Application of water to a hydrophobic surface can cause beading due to surface tension, and mixing with a suitable adjuvant can help increase the Fe absorption. A low surface tension will facilitate the close contact between the leaf surface and Fe solution, and simultaneously infiltration into stomatal cavities (Fernández et al., 2006). Rodríguez-Lucena et al. (2010) found that application of biodegradable Fe^{3+}–iminodisuccinc acid (IDS) with urea-based adjuvant can be as effective as commonly applied Fe-EDTA (ethylenediaminetetraacetic acid).

For this experiment, on-farm trials were conducted (i) to compare the effect of foliar applications of different Fe forms in 2011 and 2013 growing seasons, and (ii) to determine the suitability of different adjuvants for application with biodegradable Fe-lignosulfonate in 2014 for soybean IDC recovery and yield. We hypothesize that Fe fertilizer forms and adjuvant types would differ in solving soybean Fe deficiency depending on growing conditions and soil characteristics.

Field Experiment, Data Collection, and Analyses

On-farm field trials were conducted to determine the potential of different Fe fertilizer forms in 2011 and 2013 growing seasons and additions of adjuvants with Fe fertilizer to correct iron deficiency chlorosis of soybean in 2014. Site locations and soil characteristics are presented in Table 1. These sites have alkaline soils and were chosen based on their history of producing Fe-deficient soybeans.

During 2011 growing season, 10 different Fe fertilizer treatments were evaluated at five field sites. Ferrous lignosulfonate, ferric EDTA, ferric IDS, ferric DTPA (diethylenetriaminepentaacetic acid), and Fe-EDDHA are commercially available products (Table 2). Ferrous sulfate solution was mixed in the laboratory by adding 0.28 oz of ferrous sulfate to a 0.5-gallon volumetric flask containing ~0.26 gallons deionized water. Then, 0.02 oz of ascorbic acid was added and the solution was mixed thoroughly. Finally, the solution was brought to 0.5-gallon volume with deionized water and mixed. Ferrous EDTA was mixed in the laboratory by adding 0.37 oz of Na-EDTA and 0.02 oz ascorbic acid to ~16.9 fl oz deionized water. Approximately 30 fl oz of 0.12 lb/ft^3 NaOH solution was added to increase the pH between 6 and 7. Then, 0.28 oz of ferrous sulfate was added and ~0.64 fl oz of the NaOH solution was added to increase pH to between 6 and 7. This solution was transferred to a 0.5-gallon volumetric flask and brought to volume. Ferrous DTPA was formulated in the laboratory by first placing 0.43 oz of free acid DTPA in a beaker containing ~16.9 fl oz deionized water. While the solution stirred, ~1.5 fl oz of 0.12 lb/ft^3 NaOH was added until pH 7 was reached. Then, 0.28 oz of ferrous sulfate and 0.02 oz of ascorbic acid were added to the solution. Approximately 0.85 fl oz of NaOH was added to maintain a pH between 6 and 7. This solution was quantitatively transferred into a 0.5-gallon volumetric flask and brought to volume. During the 2013 growing season, four different commercially produced Fe-chelated fertilizers were evaluated. Four different commercially available adjuvants were tested in 2014.

Agricultural fields were scouted at the beginning of the growing season for possible sites. The locations within the field were established on the basis of visual determination of IDC development. The sites were selected where IDC development was consistent and had an approximate visual score of 2.0 and 3.0 (see below for visual score scale). Sites were established when the soybeans were in the unifoliate to first trifoliate stage. During the 2011 growing season, five field trials were conducted and soybeans were planted during the last week of May. All sites were established in fields where soybeans were planted in 22-in row spacings. The cultivars planted were 'Asgrow AG0732' with a planting population of 160,000 seeds/acre, 'Peterson 0707' with a planting population of 162,000 seeds/acre at Downer, 'Asgrow AG0401' with a planting population of 165,000 seeds/acre at Hunter, 'Dyna-Gro 37RY10RR2' with a planting population of 185,000 seeds/acre, and 'Dyna-Gro 33RY06' with a planting population of 161,000 seeds/acre at Caledonia.

Initial soil samples were analyzed for available N (9.30 lb/ft^3 KCl), Olsen-P, available K (4.91 lb/ft^3 ammonium acetate), and DTPA-Fe using standard procedure (NCR 221, 1998). Soybeans were planted according to the cultural practices

Table 1. Geographic location, initial soil properties of experimental sites located in the Red River Valley of North Dakota during the 2011, 2013, and 2014 growing seasons.

Year	Sites	Location	pH	EC†	$CaCO_3$ equivalent	SOM‡	Available N§	Available P	Available K	DTPA Fe	Soil series
				dS/m		%	lb/acre	ppm			
2011	Ada	47°21.2124′ N, 96°25.4476′ W	8.1	0.33	6.9	2.6	92	15	145	4.6	Glyndon loam
	Downer	46°36.312120′ N, 96°34.21′ W	7.7	1.72	5.5	4.9	84	8	275	5.4	Colvin silty clay loam
	Hunter	47°10.504588′ N, 97°18.4242′ W	8.2	0.36	0.8	5.3	95	4	54	5.7	Glyndon loam
	Galchutt	46°23.08142′ N, 96°59.0114′ W	8.3	0.28	10.8	1.9	75	4	80	8.7	Wyndmere loam
	Caledonia	47°27.405612′ N, 96°54.366588′ W	8.1	0.49	6.6	4.1	102	9	270	5.0	Bearden silty clay loam
2013	Ada	47°18.841′ N, 96°23.128′ W	8.3	0.25	6.78	2.99	13.6	30.3	124	6.88	Glyndon loam
	Amenia	46°51.483′ N, 97°12.843′ W	8.2	0.37	1.68	4.35	9.32	15.7	310	7.16	Wyndmere fine sandy loam
	Prosper	47°00.011′ N, 97°19.455′ W	8.0	0.31	1.51	3.68	10.1	25.8	214	8.25	Kindred silty clay loam
	Wheatland	46°42.064′ N, 97° 19.455′ W	8.0	1.58	0.42	3.88	14.6	15.5	250	6.38	Gardena silt loam
2014	Amenia_H	47°3.013′ N, 97°8.026′ W	7.9	1.48	0.92	3.10	34.5	30.5	153	6.73	Glyndon loam
	Amenia_N	47°3.013′ N, 97°8.026′ W	8.0	1.27	11.5	4.90	15.0	9.00	340	7.31	Glyndon loam
	Amenia_S	46°57.817′ N, 97°13.076′ W	8.1	0.40	1.37	3.07	17.8	7.60	296	7.09	Kindred silty clay loam
	Casselton	N 46°48.238′ 97°14.372′ W	7.7	0.69	0.37	7.22	14.3	15.5	537	14.3	Fargo silty clay
	Wheatland	N 46°44.020′ 97°23.217′ W	8.2	0.21	1.17	2.11	12.5	9.25	127	6.91	Hecla loamy fine sand

† EC, electrical conductivity.

‡ SOM, soil organic matter.

§ Available N was measured for 0- to 24-in depth for 2011 and 0- to 6-in depth for 2012 and 2013.

Table 2. Different forms of iron chelate treatments with application rate used as foliar application for three growing seasons.

Year	Treatments	Fe rate	Adjuvant	Commercial name	Manufacturer
2011	Control		Nonionic		
	Ferrous sulfate	0.89 lb/acre	Nonionic	NA†	
	Ferrous lignosulfonate	0.89 lb/acre	Nonionic	Borrechel Fe 853	Borregard Lignotech
	Ferrous EDTA	0.89 lb/acre	Nonionic	NA	
	Ferric EDTA	0.89 lb/acre	Nonionic	Librel Fe Lo	Ciba
	Ferrous IDS	0.89 lb/acre	Nonionic		Lidochem
	Ferric IDS	0.89 lb/acre	Nonionic	Krystal Klear Fe4%	Lidochem
	Ferrous DTPA	0.89 lb/acre	Nonionic	NA	
	Ferric DTPA	0.89 lb/acre	Nonionic	Sequestrene 330	Ciba-Geigy Corporation
	Ferric EDDHA	0.89 lb/acre	Nonionic	Soygreen	JAER
2013	Control		Nonionic		
	Fe EDDHA	2 oz	Nonionic	Soygreen	West Central
	Fe EDDHSA	2 oz	Nonionic	Damino Fe7%	Dadelos
	Fe Amino Acid	2.7 fl oz	Nonionic	TJ Micromix	TJ Technologies
	Fe HEDTA	2.7 fl oz	Nonionic	Feast Micro Master 4.5%	Conklin
2014	Control				
	Fe lignosulfonate‡	1.75 oz	HS MSO	Destiny HTC	WinField Solutions, ND
	Fe lignosulfonate	1.75 oz	Nonionic	R-11	Wilbur-Ellis Agribussiness, CO
	Fe lignosulfonate	1.75 oz	Acidifier	LI-700	Loveland Products, CO
	Fe lignosulfonate	1.75 oz	Organosilicone	Silwet	Helena Chemicals, TN

† NA, Solutions were prepared in the laboratory.

‡ Commercial name: (Borrechel Fe 853, Borregaard Lignotech).

of the individual farming operation where each site was established. A bicycle sprayer was used for applications. Two fertilizer applications were made. The first was applied when the IDC was first observed (first or second trifoliate stage), and the second fertilizer application was applied ~14 d after the first application. All locations were almost sprayed on the same day or next day. Solutions were applied with a bicycle wheel sprayer at first or second trifoliate stage and a backpack sprayer with 8002 flat fan nozzle spray solution (Horvick) pressurized with CO_2 at 40.39 lb/sq inch. The sprayer was cleaned with water between treatments to avoid contamination.

During 2011, visual chlorosis ratings were recorded 7 d after first spraying (first) and 7 (second) and 14 d (third) after second application of fertilizer on a 1-to-5 scale where 1 = no chlorosis and 5 = severe chlorosis (Morgan 2012). During 2013 and 2014, soil plant analysis development (SPAD) meter (Minolta SPAD-502) readings were recorded for 10 random soybean plants distributed evenly throughout the middle of each treatment. Flags were used to help ensure that the same plant and leaflet were sampled over the course of the experiment. Readings were taken just before spraying (first) and 7 (second) and 14 d (third) after the first fertilizer spraying. At the same intervals, surface soil samples (0–6 inches) were collected and analyzed for DTPA-Fe (the second sampling was skipped for 2014). Plots were harvested at physiological maturity by cutting two 10-ft rows from the two middle evaluation rows with trimmers in 2011 and by a Hege 125C combine (Wintersteiger) in 2013 and 2014. Each treatment was bagged separately and dried at 149°F for 72 h. Grain was weighed and analyzed for moisture content using a moisture analyzer (GAC 500-XT, Dickey-John Corporation).

These experiments were laid out in a randomized complete block design with four replications. Data were analyzed using analysis of variance with SAS 9.4 (SAS Institute, 2016), and LSDs were compared at the 95% significance level.

Chlorosis Ratings

Changes in chlorosis scores in response to foliar applications of Fe fertilizers and adjuvant additions are presented in Tables 3 and 4. In 2011, chlorosis was most severe at the Hunter and Caledonia sites, approaching a value of three (full interveinal chlorosis) of the upper leaves (Table 3). There was no trend for reduced chlorosis as a result of spraying soybean leaves with various Fe sources. Most of the sites were recovering from IDC, as evident from second rating (7 d after second application), but severe chlorosis ratings were still observed at the Hunter, Galchutt, and Caledonia sites. For these sites, the lowest chlorosis score was observed with the two applications of Fe-EDDHA, but the differences could not be declared to be statistically significant. For the third rating (14 d after second application), the levels of chlorosis were most severe at the Hunter site. Spraying the plants with Fe-EDDHA gave the lowest level of chlorosis at the Hunter and Caledonia sites. At the Hunter site, Fe-EDDHA,-DTPA,-EDTA, and -lignosulfonate had more significant recovery from IDC than the control.

Table 3. Changes in visual chlorosis rating at 7, 21, and 28 d after first application during the 2011 growing season.

Treatment	Sites														
	Ada			Downer			Hunter			Galchutt			Caledonia		
2011	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third
Control	2.3	1.8	1.5	2.0	1.8	1.1	2.8	3.0	3A†	2.1	2.6	1.5	2.8	1.9	1.6
Ferrous sulfate	1.9	1.6	1.1	2.0	1.6	1.0	2.8	2.9	2.8AB	2.1	2.6	1.5	2.6	2.1	1.8
Ferrous lignosulfonate	1.6	1.6	1.1	1.6	1.3	1.0	2.5	2.8	2.4BCD	2.3	2.4	1.4	2.4	2.0	1.5
Ferrous EDTA	2.0	1.5	1.1	2.0	1.8	1.1	2.9	2.4	2.4 BCD	2.5	2.5	1.6	2.4	2.1	1.9
Ferric EDTA	1.9	1.5	1.1	2.0	1.6	1.3	2.7	2.5	2.6 BC	2.4	2.4	1.6	2.8	1.9	1.6
Ferrous IDS	2.1	1.8	1.4	2.4	1.6	1.3	2.9	2.8	2.9AB	2.3	2.8	1.4	2.8	2.4	2.0
Ferric IDS	1.9	1.5	1.4	2.0	1.6	1.1	2.8	2.8	2.9 AB	2.1	2.6	1.6	2.8	2.3	1.9
Ferrous DTPA	2.1	1.6	1.0	1.9	1.5	1.1	2.6	2.6	2.8 AB	2.5	2.5	1.3	2.8	2.3	1.6
Ferric DTPA	1.9	1.6	1.3	2.1	1.8	1.1	2.8	2.6	2.3CD	2.3	2.6	1.4	2.9	2.0	1.6
Ferric EDDHA	1.9	1.9	1.3	1.9	1.4	1.0	2.8	2.3	2.1D	2.3	2.3	1.5	2.6	1.6	1.1
Significance of *F*	0.83	0.92	0.85	1.59	1.76	0.72	0.79	1.71	5.95	0.27	0.37	0.34	0.40	0.84	0.67
CV, %	20.1	15.9	27.2	15.2	15.9	19.5	11.7	13.1	9.4	22.5	19.7	34.7	20.0	23.7	35.9

† Different capital letter indicate significant difference at a 95% significance level.

Table 4. Changes in soil plant analysis development (SPAD) meter readings before spraying (first), 7 d after first spray (second), and 7 d after second (third) spraying for the 2013 and 2014 growing seasons.

	Ada			Amenia			Prosper			Wheatland					
2013	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third			
Control	26.6	33.7	40.8	35.1	39.0	43.2A†	37.8	41.8A	42.9	31.3	40.3	43.3			
Fe EDDHA	27.5	33.6	41.1	33.2	36.0	40.7B	35.8	37.5 B	42.9	29.3	40.6	44.0			
Fe EDDHSA	28.3	32.7	41.6	35.9	36.5	41.8AB	35.1	41.5AB	42.2	29.7	38.0	44.9			
Fe Amino Acid	28.1	34.7	40.4	32.8	37.9	41.3 AB	37.1	43.1A	42.5	31.3	40.1	44.1			
Fe HEDTA	29.6	35.4	41.7	35.2	36.6	42.1 AB	35.1	40.2 AB	42.7	29.3	37.4	43.6			
Significance of *F*	0.77	0.63	0.73	0.56	0.34	0.15	0.74	0.09	0.97	0.58	0.18	0.81			
CV, %	11.9	7.55	3.65	9.0	5.86	3.18	9.5	6.49	4.19	8.0	5.53	4.34			
	Amenia_H			Amenia_N			Amenia_S			Casselton			Wheatland		
2014	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third
Control	26.0	30.9	41.4	29.7	33.3	36.7	27.5	36.8 AB	39.5	30.0	39.4	42.6	28.3	33.9	41.9
HS MSO	26.6	32.0	41.2	29.1	31.4	36.4	28.3	36.4AB	38.4	29.4	38.9	43.1	26.8	34.6	41.2
Nonionic	25.4	30.2	40.8	28.5	30.6	36.1	28.3	35.1B	37.0	30.4	38.6	42.7	26.8	34.7	39.7
Acidifier	24.7	30.1	40.1	27.5	31.6	37.0	27.5	37.7A	38.9	29.9	38.1	43.3	26.7	34.5	40.7
Organosilicone	23.8	30.3	–	28.2	29.2	35.2	28.2	35.1B	37.1	29.3	38.0	44.5	26.8	34.4	37.7
Significance of *F*	0.50	0.88	0.74	0.85	0.24	0.39	0.73	0.15	0.22	0.88	0.42	0.27	0.57	0.92	0.24
CV, %	9.23	9.90	4.11	9.96	7.54	3.51	3.98	4.28	4.57	5.87	2.93	2.93	5.61	3.81	6.58

† Different capital letter indicate significant difference at a 95% significance level.

Table 5. Changes in soil available iron before (first), 7 d after first spray (second), and 7 d after second (third) spray of different forms of iron fertilizers (2013) and adjuvants (2014).

	Ada			Amenia			Prosper			Wheatland					
2013	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third			
Control	6.2B†	7.6	7.3	7.9	10.0	9.6A	8.2	10.1B	10.0	6.3	8.3	8.1			
Fe EDDHA	6.7B	8.2	7.4	6.9	9.0	9.1AB	8.1	10.6AB	10.0	6.3	8.4	8.4			
Fe EDDHSA	6.5B	7.5	7.0	6.6	8.6	8.6B	8.0	10.6AB	9.9	6.5	8.3	8.3			
Fe amino acid	7.1B	7.5	7.9	7.8	9.8	8.9B	8.4	11.8A	10.5	6.6	8.1	7.9			
Fe HEDTA	8.0A	8.2	7.8	6.7	9.1	8.2B	8.6	11.0AB	10.2	6.5	8.4	7.8			
Organosilicone	0.01	0.74	0.73	0.19	0.69	0.01	0.90	0.34	0.68	0.74	0.83	0.73			
Significance of *F*	8.44	13.6	13.7	13.0	17.1	4.84	10.4	10.8	7.0	5.40	5.34	9.70			
	Amenia_H			Amenia_N			Amenia_S			Casselton			Wheatland		
2014	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third	First	Second	Third
Control	6.5AB		6.3	7.9		6.1	7.3		5.7	14.4		11.7	5.9		4.9
HS MSO	6.1B		6.2	7.2		6.7	7.4		5.5	14.1		10.9	7.8		7.2
Nonionic	6.5 AB		6.2	7.3		6.1	7.3		5.8	14.2		11.0	6.3		12.8
Acidifier	7.6A		6.5	7.3		6.3	6.9		5.1	14.8		12.5	7.9		7.6
Organosilicone	7.0 AB		6.6	7.0		6.2	6.7		5.2	14.0		10.4	6.7		6.2
Organosilicone	0.09		0.64	0.72		0.28	0.29		0.48	0.80		0.21	0.49		0.77
Significance of *F*	11.0		6.33	0.49		6.14	7.38		11.7	6.81		11.1	27.8		11.6

† Different capital letter indicate significant difference at a 95% significance level.

Also at Caledonia, Fe-EDDHA had the least chlorosis, but the degree of chlorosis was very slight.

In 2013, Ada had the lowest initial SPAD reading as compared with other sites, and SPAD reading improved over time (Table 4). At Amenia, the control had a higher SPAD reading than Fe-EDDHA at the second reading, but the difference disappeared at the third reading. Overall, foliar application of Fe sources had little effect on SPAD readings across sites. During 2014, application of adjuvants also did not make any significant difference in SPAD; except at Amenia_S, acidifier adjuvant had significantly higher SPAD reading than nonionic and organosillicone on second observation, but it did not persist.

Previous field studies also indicated mixed results in correcting soybean-IDC with foliar application of Fe (Goos and Johnson, 2000; Franzen et al., 2003; Lingenfelser et al., 2005). Greenhouse experiments attempting to correct IDC indicate that leaves can be regreened with foliar applications of Fe; however, these results were not always significantly different from a control with Fe provided in the nutrient solution (Rodríguez-Lucena et al., 2010). Fernández et al. (2006) also observed that alkyl-glucoside 2, a nonionic surfactant, markedly improved the effectiveness of foliar Fe fertilization and leaf regreening as compared with Fe-carrier solutions alone in peach [*Prunus persica* (L.) Batsch].

Soil Iron Availability

Changes in soil available Fe over the growing season are presented in Table 5 for 2013 and 2014. At Ada in 2013, significant differences among treatments before spraying (first observation) indicate spatial variability in Fe availability. At Prosper, Fe-amino acid had higher soil Fe availability over the control after first spray. However, at the Amenia site, the control had significantly higher Fe availability than most of the Fe sources, except Fe-EDDHA at third observation, where the control still had higher Fe availability. In 2014, addition of adjuvants had no effect on Fe availability across sites (except soil Fe availability before spraying at the Amenia_H site).

Soybean Yield

Foliar applications of different Fe fertilizer forms and adjuvants did not increase yield over the control across

Table 6. Soybean yield in response to different foliar iron fertilizer sources during 2011, 2013, and 2014 growing seasons.

Treatment	Sites				
2011	Ada	Downer	Hunter	Galchutt	Caledonia
	bu/acre				
Control	45.7	40.9	3.6	25.0	27.9
Ferrous sulfate	52.5	40.3	5.7	31.1	25.3
Ferrous lignosulfonate	53.0	41.6	5.9	30.0	31.8
Ferrous EDTA	51.1	38.9	6.6	30.8	27.2
Ferric EDTA	51.9	37.6	3.7	30.5	27.4
Ferrous IDS	48.3	35.8	6.8	35.1	23.0
Ferric IDS	50.3	39.1	6.3	23.1	28.0
Ferrous DTPA	52.3	39.5	5.3	30.9	26.6
Ferric DTPA	50.9	41.2	5.8	29.7	27.6
Ferric EDDHA	49.0	41.6	9.4	28.0	31.9
Significance of *F*	0.90ns†	1.20ns	1.80ns	1.11ns	0.61ns
CV, %	9.5	8.6	41.4	21.7	24.7
2014	Ada	Amenia	Prosper	Wheatland	
Control	29.2	20.6	40.6	16.6	
Fe EDDHA	27.9	22.0	40.1	18.4	
Fe EDDHSA	29.0	20.8	38.4	18.5	
Fe Amino Acid	29.0	17.4	39.4	14.6	
Fe HEDTA	30.3	22.2	37.3	18.8	
Significance of *F*	0.68ns	0.67ns	0.75ns	0.55ns	
CV, %	7.7	24.1	10.0	22.8	
2015	Amenia_H	Amenia_N	Amenia_S	Casselton	Wheatland
Control	21.3	30.4	36.1	20.5	35.3
HS MSO	17.3	26.6	35.3	21.6	35.5
Nonionic	21.6	23.3	36.3	19.9	34.9
Acidifier	21.3	27.8	37.0	20.0	34.6
Organosilicone	14.3	20.1	36.7	23.1	31.6
Significance of *F*	0.70ns	0.14ns	0.87ns	0.39ns	0.37ns
CV%	45.5	21.7	6.85	12.1	8.63

† ns, nonsignificant at a 95% significance level.

experimental sites and growing seasons (Table 6). However, plots receiving Fe fertilizers had higher yield than the control at four out of five sites in 2011 (except Caledonia). There was a weak trend for yields to be improved by Fe applications in general at the Ada site, but differences were not significant at a 95% significance level. At Hunter, IDC was severe and yields were <10 bu/acre. Two spray applications of Fe did not improve yield over the control. Application of two sprays of Fe-EDDHA increased yield from 3.6 to 9.4 bu/acre, which was not statistically significant. This outcome at Hunter clearly illustrates the challenges of controlling IDC with foliar sprays. In 2013, Fe-HEDTA had the highest yield for three out of four sites. Adjuvant additions had no effect on yield in 2014, but the highest yield was observed under treated plot across five sites. The highest yield was observed with acidifier at Amenia_N and Amenia_S, with nonionic at Amenia_H, with organosilicone at Casselton, and with HS MSO at Wheatland.

Our study indicates that foliar applications of Fe fertilizer forms and adjuvants might have an effect on regreening of leaves, but soybean yield did not significantly improve over the control. Except for the Prosper site in 2013, highest yield was always observed with treated plots, and this indicates a positive effect of Fe fertilizers. Selection of IDC-resistant cultivars has been shown to the most effective management practice thus far (Goos and Johnson 2000). Integrating cultivar selection with other management practices like planting in areas with low nitrate levels (Wiersma, 2010; Bloom et al., 2011), increasing seed rates (Goos and Johnson, 2001), and using Fe-EDDHA fertilizer with seed at planting (Wiersma, 2005) have performed better than foliar sprays on fields prone to IDC.

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