FERTILIZER MANAGEMENT

Correcting Iron Deficiency in Corn with Seed Row–Applied Iron Sulfate

Chad B. Godsey,* John P. Schmidt, Alan J. Schlegel, Randal K. Taylor, Curtis R. Thompson, and Ronald J. Gehl

ABSTRACT

Corn (*Zea mays* L.) grown on calcareous, high-pH soils is susceptible to Fe deficiency, which can reduce grain yield by as much as 20%. The objective of this study was to evaluate several treatments of $FeSO_4$ that could be used with precision-farming technologies to alleviate Fe deficiency in irrigated corn. Three sites in 1999 and four in 2000 were selected (based on a history of Fe deficiency) for small-plot (3 by 12.2 m) studies in western Kansas. In 1999, five treatments, including four rates of $FeSO_4{\cdot}H_2O$ (0–81 kg ha^{-1} product) applied in the seed row and one foliar treatment (chelated Fe), were evaluated. In 2000, two additional treatments, $CaSO_4{\cdot}2H_2O$ (85 kg ha^{-1} product) and liquid $FeSO_4{\cdot}7H_2O$ (91 kg ha^{-1} product) applied in the seed row, were included. Grain yield increased linearly with increasing rates of $FeSO_4{\cdot}H_2O$ at four of seven site-years, increasing 0.02 Mg ha^{-1} for each kilogram per hectare of $FeSO_4{\cdot}H_2O$ applied. Based on yield responses observed in this study, 81 kg ha^{-1} $FeSO_4{\cdot}H_2O$ was the most consistent treatment for correcting Fe deficiency in corn. If the average yield response obtained in this study can be achieved on 15% of an individual cornfield, the expected return would be \$3.00 ha^{-1} for the entire field. Current precision-farming technologies allow application of $FeSO_4{\cdot}H_2O$ only to areas susceptible to Fe deficiency. Employing these technologies provides a practical solution to the spatial heterogeneity of Fe deficiency in irrigated corn and increases the probability of crop response to the fertilizer application.

During the last few decades, numerous attempts have been made to develop a practical solution for treating Fe deficiency, including many Fe-containing fertilizers and different placement strategies of these fertilizers. Treatments have been identified that help correct Fe deficiency, but few have been found that were economically feasible as whole-field treatments for corn and grain sorghum [*Sorghum bicolor* (L.) Moench] production. The most widely used Fe sources are inorganic Fe forms and chelates mixed with inorganic Fe forms (Vempati and Loeppert, 1986). Chelated forms of Fe are usually more effective in reducing Fe chlorosis than are inorganic forms. However, chelates are rarely economically feasible for low-value crops such as corn and grain sorghum because treatments often have to be repeated several times during a growing season.

One of the most widely used methods for correcting Fe deficiency is foliar application of Fe solutions. This method of correction usually alleviates chlorosis; however, the results from a foliar application may be only temporary and actually depress the plant's Fe stress mechanisms by preventing the increase in Fe-reducing capacity of the roots that would normally occur during Fe deficiency (Römheld and Marschner, 1986b). Other intensively researched Fe sources include organic compounds, acidifying amendments, industrial by-products, and animal wastes (Olson, 1950; Wallace et al., 1976; Thomas and Mathers, 1979).

Researchers are faced with many challenges when working with Fe fertilizer. Cihacek (1984) observed that researchers find mixed results because treatments often show little or no visual effect on Fe chlorosis, grain yields vary from year to year, or effective treatments are not economically feasible for the producer. Numerous factors contribute to the inconsistent results, but perhaps the two biggest obstacles to overcome are temporal and spatial variability. Temporal variability can be induced by variability in climatic conditions that affect soil temperature and soil moisture and cause inconsistent treatment responses. Spatial heterogeneity creates problems because Fe-deficient areas in a field are usually small and levels of plant-available soil Fe can vary within a few meters (Vempati and Loeppert, 1986). Evaluation of treatments in these areas is difficult because levels of plant-available soil Fe can vary within a plot and cause inconsistent treatment response within the plot.

A commonly used fertilizer for the correcting Fe chlorosis is ferrous sulfate ($FeSO_4{\cdot}H_2O$ or $FeSO_4{\cdot}7H_2O$). Researchers have demonstrated that the addition of $FeSO_4$ increases grain yield of corn and grain sorghum grown on Fe-deficient soil. In Nebraska, Hergert et al. (1996) observed an increase in corn grain yield of nearly 3.6 Mg ha^{-1} on two soils with pH greater than 8.2 by placing 85 kg ha^{-1} $FeSO_4{\cdot}7H_2O$ directly in the seed row. They also observed a greater response to $FeSO_4{\cdot}7H_2O$ at sites with a soil pH greater than 8.0 compared to a site with a soil pH of 7.7. Mathers (1970) indicated that 112 kg ha^{-1} $FeSO_4{\cdot}7H_2O$ banded 20 cm beneath the soil surface and directly under the seed increased grain sorghum yield by 1.0 Mg ha^{-1} compared with the control treatment. However, some researchers have experienced mixed results with the addition of $FeSO_4{\cdot}7H_2O$. Yield response varies greatly from year to year, and some research has indicated no significant response to the addition of $FeSO_4{\cdot}7H_2O$ (Olson, 1950; Mortvedt and Gi-

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C.B. Godsey, J.P. Schmidt, and R.J. Gehl, Dep. of Agron., and R.K. Taylor, Dep. of Biol. and Agric. Eng., Kansas State Univ., Manhattan, KS 66506; A.J. Schlegel, Southwest Res. and Ext. Cent., Kansas State Univ., Tribune, KS 67879; Kansas State Univ., Manhattan, KS 66506; and C.R. Thompson, Southwest Res. and Ext. Cent., Kansas State Univ., Garden City, KS 67846. Kansas Agric. Exp. Stn. Contrib. no. 02-110-J. Received 2 Jan. 2002. *Corresponding author (cgodsey@ksu.edu).

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Abbreviations: DTPA, diethylenetriaminepenta-acetic acid; GPS, global positioning system; OM, organic matter.

ordano, 1970). Olson (1950) found that 1120 kg ha^{-1} $FeSO_4{\cdot}7H_2O$ mixed with an Fe-deficient soil did not significantly increase aboveground dry matter of grain sorghum in a greenhouse study. The effectiveness of this treatment may be determined by soil factors and the placement of the $FeSO_4{\cdot}7H_2O$. Effective $FeSO_4$ treatments mentioned above were either placed in a concentrated band near or with the seed while the ineffective treatments were mixed with the soil. Iron sulfate added to calcareous soils quickly reacts with $CaCO_3$ to form Fe oxides that are less available for plant uptake. By concentrating $FeSO_4$ in a band, the Fe is possibly available longer for plant uptake, compared with Fe that is mixed throughout the soil, because of less fertilizer to soil contact. Soil factors that determine the effectiveness of the $FeSO_4$ include soil texture, pH, and $CaCO_3$ content (Vempati and Loeppert, 1988).

Soils with high pH that exhibit Fe deficiency present a problem for producers in low-rainfall climates throughout the world. Problems such as spatial heterogeneity of Fe-deficient areas within a field, availability of an effective remedy, and affordability of treatments have limited the success of many potential solutions. Current precision-farming technologies can be used to address some of these problems, especially the spatial heterogeneity of problematic areas.

The objective of this research was to evaluate several treatments of ferrous sulfate that could be used with precision-farming technologies to minimize the economic loss caused by Fe deficiency in irrigated corn in the Great Plains.

MATERIALS AND METHODS

Field studies were conducted at five locations in western Kansas in 1999 and 2000 (seven site-years). These sites were selected because they had a history of exhibiting Fe chlorosis in corn (relatively lower yields for multiple years), and the presence of $CaCO_3$ could be visually observed on the soil surface. Soils at these sites developed from silty to sandy sediments or windblown material (Table 1). Pioneer hybrid '3489' (susceptible to Fe deficiency) was planted at a density of 75 582 seeds ha^{-1} at each site. The Finney County site was flood-irrigated, and all other sites were center pivot–irrigated. All N, P, and K fertilizer; water; and herbicide scheduling was determined by individual producers and were typical for this area with exceptions noted.

Soil samples were collected before planting each year from each location. One core (2.5-cm i.d., 0- to 20-cm depth) was obtained from each individual plot to make a composite sample for each site. A representative subsample of this composite was oven-dried at 60°C and then ground to pass through a 2-mm sieve. Soil samples were analyzed for pH, Bray-1 P (Frank et al., 1998), Olsen P (Frank et al., 1998), extractable K (1 *M* NH_4OAc at pH 7; Warncke and Brown, 1998), diethylenetriaminepenta-acetic acid (DTPA) Fe (Whitney, 1998), and $CaCO_3$ content. Calcium carbonate content was determined using a LECO CNS analyzer (LECO, St. Joseph, MI) (Nelson and Sommers, 1996) by determining C as $CaCO_3$. The samples were first analyzed for percentage of total C. Samples were then treated with 1 mL of 1.2 *M* HCl, allowed to stand for 12 h, and analyzed for percentage of organic C. Percentage of C, as $CaCO_3$, was determined from the difference between total C and organic C.

1999

Treatments included four rates of $FeSO_4{\cdot}H_2O$ (0, 27, 54, and 81 kg ha^{-1} product) applied in the seed row and one foliar application in a randomized complete block design with four blocks. Each plot was 3 m wide (four 0.76-m-wide rows) and 12.2 m long. All plots received 65 L ha^{-1} ammonium polyphosphate (APP) fertilizer (10–34–0) applied in the seed row. The $FeSO_4{\cdot}H_2O$ was placed in the seed slot through insecticide boxes on a JD 7300 (John Deere Co., Moline, IL) planter. The foliar Fe source used was Nortrace hydroxyethylenediaminetri-acetic acid (HEDTA; 4.5% chelated Fe; RSA Microtech, Seattle, WA). The treatment was applied at growth stage V4 (Ritchie et al., 1989) at a rate of 1.9 L ha^{-1} product (0.15 kg ha^{-1} Fe) in 187 L ha^{-1} H_2O with 0.25% (v/v) nonionic surfactant. Grain yield was determined by hand-harvesting a 12-m length (two 6-m segments) of row from the middle two rows of each plot. Corn was shelled with a spike cylinder sheller and then weighed. Yields were adjusted to 155 g kg^{-1} moisture content.

2000

Two additional treatments were included in the small-plot studies in 2000. The additional treatments were calcium sulfate ($CaSO_4{\cdot}2H_2O$) applied at a rate of 85 kg ha^{-1} and a liquid $FeSO_4{\cdot}7H_2O$ treatment. Unlike 1999, all $FeSO_4{\cdot}H_2O$ and $CaSO_4{\cdot}2H_2O$ treatments were applied with Gandy PDM fertilizer boxes (Gandy Co., Owatonna, MN) mounted on the planter toolbar. The $FeSO_4{\cdot}H_2O$ and $CaSO_4{\cdot}2H_2O$ were placed directly in the seed row by running a hose from the Gandy box directly in front of the press wheels on the planter. The $FeSO_4{\cdot}7H_2O$ was mixed with water at a concentration of 0.24 kg L^{-1} $FeSO_4{\cdot}7H_2O$ mixed with 65 L ha^{-1}10–34–0 and applied at a total rate of 380 L ha^{-1} for the combined products. This was equivalent to the amount of Fe applied with 68.0 kg ha^{-1} $FeSO_4{\cdot}H_2O$. The Finney site received a similar treatment of liquid $FeSO_4{\cdot}7H_2O$ that was applied at a rate equivalent to

Table 1. General site characteristics.

Field	Location	Soil series†	Taxonomic classification	Parent material
			1999	
Finney	**Finney Co., KS**	**Ulysses silt loam**	**Fine-silty, mixed, superactive, mesic Aridic Haplustolls**	**Silty sediments or loess**
Scott	**Scott Co., KS**	**Ulysses silt loam**	**Fine-silty, mixed, superactive, mesic Aridic Haplustolls**	**Silty sediments or loess**
SE14	**Stevens Co., KS**	**Ulysses silt loam**	**Fine-silty, mixed, superactive, mesic Aridic Haplustolls**	**Silty sediments or loess**
			2000	
Finney	**Finney Co., KS**	**Manter fine sandy loam**	**Coarse-loamy, mixed, superactive, mesic Aridic Argiustolls**	**Sandy sediments**
NW33	**Stevens Co., KS**	**Dalhart fine sandy loam**	**Fine-loamy, mixed, superactive, mesic Aridic Haplustalfs**	**Sandy and deposited by wind**
SE14	**Stevens Co., KS**	**Richfield silt loam**	**Fine, smectitic, mesic Aridic Argiustolls**	**Loess or similar silty sediments**
SW29	**Stevens Co., KS**	**Dalhart fine sandy loam**	**Fine-loamy, mixed, superactive, mesic Aridic Haplustalfs**	**Sandy and deposited by wind**

† Sources include USDA county soil surveys as follows: Finney, Soil Survey Staff (1965a); Scott, Soil Survey Staff (1965b); NW33, SE14, and SW29, Soil Survey Staff (1961).

Table 2. Selected soil characteristics.

Location	pH	Bray-1 P	Olsen P	Extractable K†	DTPA‡-Fe	OM§	$CaCO_3$
		mg kg^{-1}				g kg^{-1}	
				1999			
Finney	8.3	0	6	480	3	14	59
Scott	7.9	7	24	735	3	24	51
SE14	8.1	4	10	364	4	19	100
				2000			
Finney	8.2	0	8	487	2	12	62
NW33	8.2	1	10	346	3	14	103
SE14	8.0	2	9	429	3	20	111
SW29	8.0	40	33	450	3	15	26

† Extractable K (1 *M* NH_4OAc at pH 7; Warncke and Brown, 1998).
‡ DTPA, diethylenetriaminepenta-acetic acid.
§ OM, organic matter.

the amount of Fe applied with 81 kg ha^{-1} $FeSO_4{\cdot}H_2O$; however, the Finney site did not receive the 10–34–0. Plot size was the same as in 1999. Sites that were repeated in 2000 were not in the same exact location but in the same general area of the same field as in 1999.

Leaf tissue or whole-plant tissue samples were collected at the V4, V8, and V12–VT growth stages from each plot. Plant tissue samples were prepared using the perchloric digest, and then Fe concentration was determined with an atomic adsorption spectrometer (PerkinElmer Corp., Shelton, CT; Geiseking et al., 1935). Twenty V4 whole-plant tissue samples were collected randomly regardless of plant characteristics. Ten V8 whole-plant tissue samples were collected randomly and chopped before drying. Ten leaf tissue samples were collected randomly at the V12–VT growth stage by selecting the most recently mature leaf. Tissue samples were collected from the outside row on both sides of the plot. All tissue samples were dried at 60°C and ground to pass through a 0.5-mm stainless steel sieve.

Small-plot grain yield was determined for the Finney, NW33, and SE14 sites using a Gleaner E combine modified for experimental plots. The middle two rows of each plot were harvested and weighed. At SW29, small-plot grain yield was determined by hand-harvesting the entire plot. Each plot was subdivided into four subplots that were 3 m long and 3 m wide, and yields from subplots were averaged to obtain an average yield for each plot (four rows). Corn was shelled with a spike cylinder sheller, weighed, and yields adjusted to 155 g kg^{-1} moisture content.

Statistical analyses were performed on data from both years using General Linear Procedures (PROC GLM; SAS Inst., 1998) to analyze treatment differences in grain yield and Fe concentrations in tissue samples for individual sites. When data from more than one location were combined across years, PROC MIXED (SAS Inst., 1998) was used to analyze treatment differences in grain yield. Selected contrasts were used in PROC GLM and PROC MIXED for specific treatment comparisons. Linear response models were evaluated using PROC REG (PROC GLM; SAS Inst., 1998) procedures.

RESULTS AND DISCUSSION

Soil characteristics (Table 2) at all sites were typical of soils susceptible to Fe deficiency in corn and similar to those from other Fe fertility research studies for irrigated corn in the Great Plains (Hergert et al., 1996). In general, pH ranged between 7.9 and 8.3, which corresponds to the pH range of minimum total Fe solubility (Lindsay, 1984). The DTPA-extractable Fe, which ranged from 2 to 4 mg kg^{-1}, was less than the critical threshold of 4.5 mg kg^{-1}. Below this threshold, Kansas State University recommends Fe fertilizers for irrigated corn (Whitney, 1983). Another important soil characteristic associated with all sites is the presence of $CaCO_3$. Calcium carbonate content ranged from 26 to 111 g kg^{-1} (Table 2). The presence of $CaCO_3$ adversely affects naturally occurring Fe uptake mechanisms (Loeppert et al., 1994) when $CaCO_3$, in equilibrium with CO_2 in the root atmosphere, causes a higher HCO_3^- concentration in the soil solution relative to $CaCO_3$–free soils. High HCO_3^- is believed to inhibit Fe absorption by the root as well as translocation within the plant (Römheld et al., 1982; Dofing et al., 1989; Loeppert et al., 1994).

The most consistent treatment response that was detected from individual sites was the linear increase in grain yield due to the addition of $FeSO_4{\cdot}H_2O$ (Tables 3 and 4). In 1999, grain yield at SE14 and Finney increased 0.02 and 0.01 Mg ha^{-1}, respectively, with each kilogram per hectare of $FeSO_4{\cdot}H_2O$ applied (Table 5). In 2000, the addition of $FeSO_4{\cdot}H_2O$ increased grain yield by 0.02 Mg ha^{-1} with each additional increment (kg ha^{-1}) of

Table 3. Selected contrasts for grain yield at individual sites.

	1999			2000			
Contrast	**Finney**	**Scott**	**SE14**	**Finney**	**NW33**	**SE14**	**SW29**
				$P > F$			
$FeSO_4{\cdot}H_2O$ (linear)	0.09	0.50	0.09	0.58	0.08	0.88	0.12
$FeSO_4{\cdot}H_2O$ (quadratic)	0.17	0.26	0.66	0.28	0.64	0.09	0.99
liquid $FeSO_4{\cdot}7H_2O$ vs. $FeSO_4{\cdot}H_2O$ (54 and 81 kg ha^{-1})	na†	na	na	0.82	0.22	0.73	0.22
liquid $FeSO_4{\cdot}7H_2O$ vs. control	na	na	na	0.31	0.01	0.31	0.86
$FeSO_4{\cdot}H_2O$ (81 kg ha^{-1}) vs. $CaSO_4{\cdot}2H_2O$	na	na	na	0.79	0.47	0.04	0.22
$CaSO_4{\cdot}2H_2O$ vs. control	na	na	na	0.89	0.24	0.01	0.72
foliar Fe vs. control	0.62	0.55	0.17	0.75	0.94	0.62	0.61

† Not applicable. Liquid $FeSO_4{\cdot}7H_2O$ and $CaSO_4{\cdot}2H_2O$ were not included as treatments in 1999.

Table 4. Average corn grain yield in 1999 and 2000.

		Treatments							
		$FeSO_4 \cdot H_2O$ (kg ha^{-1})					$CaSO_4 \cdot 2H_2O$ (kg ha^{-1})	$FeSO_4 \cdot 7H_2O$ (kg ha^{-1})	
Year	**Site**	**0**	**27**	**54**	**81**	**Foliar**	**85**	**68**	**SE†**
		Mg ha^{-1}							
1999	Finney	9.8	10.5	9.3	11.3	10.1	na‡	na	0.41
	Scott	11.9	12.5	12.6	12.3	11.5	na	na	0.41
	SE14	11.1	12.2	12.2	12.8	12.4	na	na	0.61
2000	Finney	9.5	9.2	8.9	9.3	9.3	9.2	9.0	0.59
	NW33	7.3	8.6	8.5	9.2	7.2	8.5	9.9	0.69
	SE14	9.7	8.8	9.3	9.5	9.9	8.6	9.3	0.27
	SW29	9.6	10.2	10.6	11.0	9.2	9.9	10.3	0.56
Average§		9.8	10.3	10.2	10.7	9.9	10.0¶	10.5¶	

† Standard error.

‡ Not applicable. The liquid $FeSO_4 \cdot 7H_2O$ and $CaSO_4 \cdot 2H_2O$ treatments were not included as a treatment in 1999.

§ The treatment average of all seven sites included in this study.

¶ Derived from LSMEAN statement in PROC MIXED (SAS Inst., 1998).

$FeSO_4 \cdot H_2O$ at NW33 (Table 5). Another notable response to the addition of $FeSO_4 \cdot H_2O$ was at SW29 in 2000. Although the probability of exceeding F at SW29 was slightly above the 0.10 level, this site was considered a *responsive* site because the trend was more similar to that observed at Finney (1999), SE14 (1999), and NW33 (2000) compared with the other three sites. In addition, the slopes of the linear relationship for these sites were not statistically different from the average response, $\beta_o = 0.02$ (using the criterion $P > F \leq 0.10$), while the slopes of these same relationships for the nonresponsive sites were statistically different from $\beta_o = 0.02$.

A negative quadratic yield response to $FeSO_4 \cdot H_2O$ was detected at SE14 in 2000 (Table 5); however, this negative response was probably a consequence of the relatively high yield for the control treatment (Table 4) and is not biologically relevant ($r^2 = 0.04$).

Grain yield increased 2.6 Mg ha^{-1} at NW33 (2000) from the addition of $FeSO_4 \cdot 7H_2O$ compared with the control (Tables 3 and 4). However, when comparing $FeSO_4 \cdot H_2O$ (54 and 81 kg ha^{-1}) to the liquid $FeSO_4 \cdot 7H_2O$ treatment, a difference in grain yield was not detected.

Contrasting $FeSO_4 \cdot H_2O$ (81 kg ha^{-1}) to $CaSO_4 \cdot 2H_2O$ resulted in one significant difference at the sites evaluated in 2000 (Table 3). At SE14 (2000), average grain yield from the addition of $FeSO_4 \cdot H_2O$ was 0.9 Mg ha^{-1} greater than the $CaSO_4 \cdot 2H_2O$ treatment (Table 4).

Table 5. Grain yield as a function of $FeSO_4 \cdot H_2O$ at sites where yield was significantly affected by increasing $FeSO_4 \cdot H_2O$ in 1999 and 2000.

Site	Year	Function	r^2†
SE14	1999	$Y = 0.02x + 11.3$	0.31
Finney	1999	$Y = 0.01x + 9.7$	0.42
NW33	2000	$Y = 0.02x + 7.6$	0.83
SW29	2000	$Y = 0.02x + 9.7$	0.29
SE14	2000	$Y = 0.0004x^2 - 0.0309x + 9.6$	0.04

† The r^2 values were calculated using all the grain yield observations at each site.

Table 6. Selected contrasts† for grain yield with sites combined. The dependent variable is grain yield.

Contrast	$P > F$
$FeSO_4 \cdot H_2O$ (linear)	0.01
$FeSO_4 \cdot H_2O$ (quadratic)	0.84
Liquid $FeSO_4 \cdot 7H_2O$ vs. $FeSO_4 \cdot H_2O$ (54 and 81 kg ha^{-1})	0.77
Liquid $FeSO_4 \cdot 7H_2O$ vs. control	0.05
$FeSO_4 \cdot H_2O$ (81 kg ha^{-1}) vs. $CaSO_4 \cdot 2H_2O$	0.04
$CaSO_4 \cdot 2H_2O$ vs. control	0.67
Foliar Fe vs. control	0.71

† Evaluated in PROC MIXED (SAS Inst., 1998).

Grain yield from the addition of the foliar Fe did not increase grain yield compared with the control at any of the individual sites (Table 3).

The most notable treatment result observed from all seven site-years combined was a linear increase in grain yield with increasing amounts of $FeSO_4 \cdot H_2O$ (Table 6). The addition of $FeSO_4 \cdot H_2O$, when data from all seven site-years were combined, resulted in a 0.01 Mg ha^{-1} increase in grain yield for every additional kilogram per hectare of $FeSO_4 \cdot H_2O$ (Fig. 1).

These field sites can be divided into two categories, responsive sites where grain yield increased linearly with increasing amounts of $FeSO_4 \cdot H_2O$ and nonresponsive sites where yield was unaffected by the addition of $FeSO_4 \cdot H_2O$. In four out of seven site-years [SE14 (1999), Finney (1999), SW29 (2000), and NW33 (2000)], grain yield increased 0.02 Mg ha^{-1} with each kilogram per hectare of $FeSO_4 \cdot H_2O$ applied (Fig. 2).

Grain yield response to the addition of $FeSO_4 \cdot H_2O$ was similar to results reported by Hergert et al. (1996). They reported that placing 170 kg ha^{-1} $FeSO_4 \cdot 7H_2O$ with the seed at planting increased grain yield by almost 3.6 Mg ha^{-1} for a nontolerant hybrid compared with yield for the control treatment. However, similar to results reported in this study, inconsistency in the re-

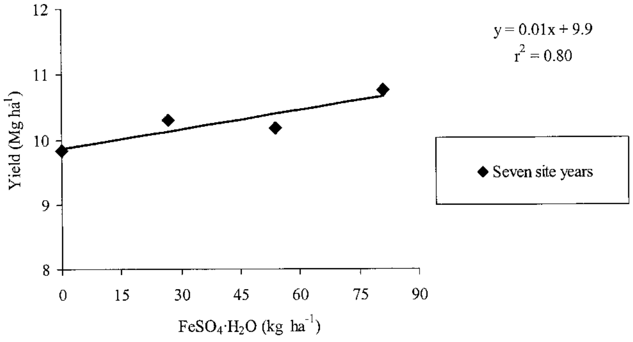

Fig. 1. Average grain yield as a function of increasing $FeSO_4 \cdot H_2O$ for all seven site-years. The r^2 was determined by using the average grain yield from every treatment.

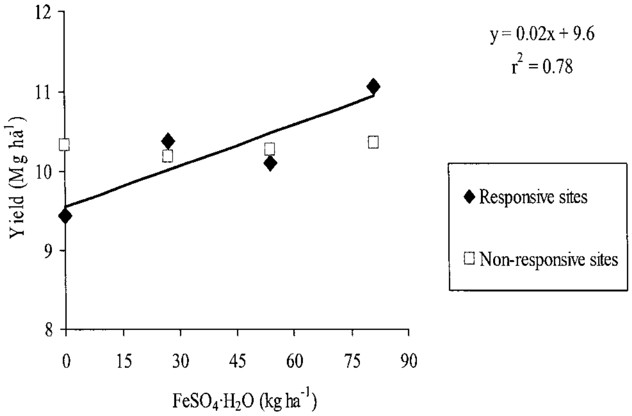

Fig. 2. Grain yield as a function of increasing $FeSO_4 \cdot H_2O$ at responsive sites [SE14 and Finney (1999) and SW29 and NW33 (2000)] and nonresponsive sites [Scott (1999) and Finney and SE14 (2000)]. The r^2 was determined by using the average grain yield from every treatment.

sponse to $FeSO_4$ was also noted by Hergert et al. (1996), with considerable variation among sites. The addition of 85 kg ha^{-1} $FeSO_4 \cdot 7H_2O$ increased grain yield by 4.1 Mg ha^{-1} at one field site while a response to the treatment was not observed at two other field sites (Herget et al., 1996).

The inconsistent response between years at specific sites was difficult to attribute to a specific factor. At SE14 in 2000, the lack of favorable response to the addition of $FeSO_4 \cdot H_2O$, compared with the response observed for this site in 1999 (Table 3), may have been a consequence of lower-than-average rainfall during the 2000 growing season (Fig. 3). Even though all sites were irrigated, additional precipitation is usually considered beneficial during this period of rapid growth (June through July) due to high water demand by the crop. The below-average precipitation may have prevented the corn from reaching maximum yield potential, thereby possibly minimizing the potential yield response from the addition of $FeSO_4 \cdot H_2O$.

A similar argument could be made for the lack of response at Finney in 2000 compared with the favorable response observed in 1999 (Table 3). In 2000, corn in the small-plot study was planted 14 d later than the rest of the field. Due to this later planting date, corn in the small-plot study was usually one growth stage behind the rest of the field throughout the growing season. When the majority of the field reached physiological maturity, flood irrigation was stopped even though corn located in the small plot was not yet physiologically mature. An inadequate water supply during later stages of ear development may have limited yield potential.

When liquid $FeSO_4 \cdot 7H_2O$ was applied, the contrast comparing $FeSO_4 \cdot 7H_2O$ to the control indicated that the liquid $FeSO_4 \cdot 7H_2O$ treatment significantly increased grain yield over the control by 0.7 Mg ha^{-1} (Table 6); however, this result may be a slight overstatement or at least premature. Because the liquid $FeSO_4 \cdot 7H_2O$ treatment was not evaluated in 1999, the means were contrasted by com-

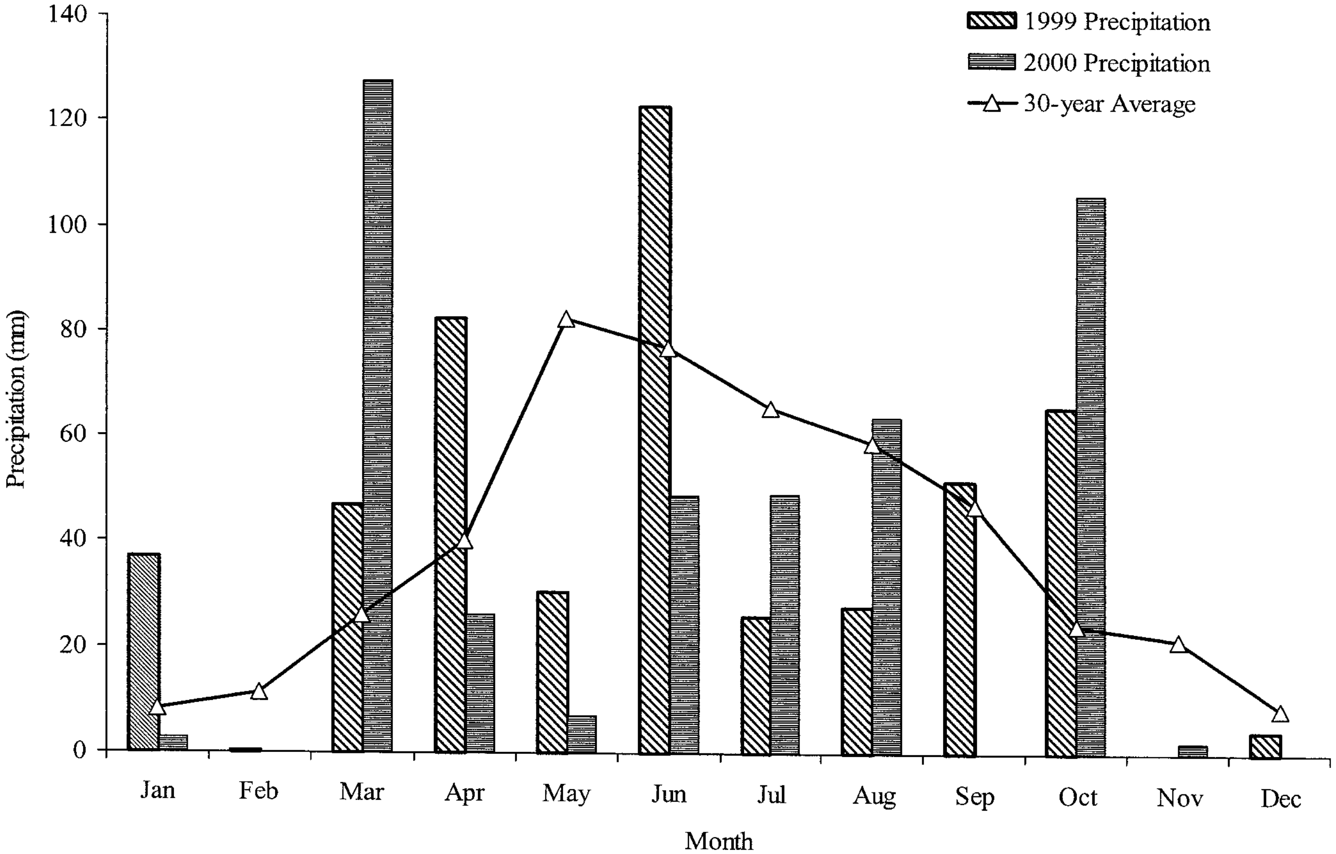

Fig. 3. Monthly precipitation amounts for Hugoton, KS (Stevens County) (Weather Data Library, Kansas State Univ., Manhattan).

bining results from both years, as estimated in PROC MIXED (SAS Inst., 1998). By treating the location as a random effect, PROC MIXED (SAS Inst., 1998) can make appropriate block adjustments to the LSMEANS (SAS Inst., 1998) without having each treatment present in each block.

Grain yield as a result of the foliar Fe treatment applied at the V4 growth stage was never different from yield for the control treatment (Table 3). The lack of response from the foliar Fe treatment was not surprising because foliar treatments are believed to actually depress the plant's Fe stress mechanisms by preventing the increase in reducing capacity of the roots that occurs during Fe deficiency (Römheld and Marschner, 1986a). However, if the foliar treatment is applied repeatedly (2-wk intervals) when visual symptoms are present, the foliar application may help alleviate Fe deficiency in corn (Whitney, 1983). Repeated foliar Fe applications are not a typical management practice for corn production because the cost is usually too great compared with the return from this treatment.

The $CaSO_4{\cdot}2H_2O$ treatment was added in 2000 to determine whether yield responses were attributable to S additions with the $FeSO_4{\cdot}H_2O$ rather than the Fe. The $CaSO_4{\cdot}2H_2O$ treatment did not increase grain yield compared with the control treatment (Tables 3 and 4). A water sample collected from the irrigation water at SW29 on 12 July 2000 contained 70 mg L^{-1} SO_4–S, which corresponds to approximately 426 kg ha^{-1} S applied each growing season, assuming 610 mm of water applied during the growing season. Sulfur content in the water sample at SW29 was probably representative of S content from the other wells. Consequently, the increase in grain yield observed with the $FeSO_4$ treatments was probably not a result of the additional S.

Tissue samples were collected at three different vegetative growth stages (V4, V8, and V12) for the four sites in 2000. The severity of visual symptoms of chlorosis varied among sites, but visual symptoms were present at all sites at all three growth stages. However, differences were visually indistinguishable among Fe treatments. Average Fe concentrations in leaf tissue taken at V12 were significantly greater ($P > F = 0.09$) with the addition of $FeSO_4{\cdot}7H_2O$ at all four sites in 2000. Iron concentration for the $FeSO_4{\cdot}7H_2O$ treatment (64.5 mg kg^{-1}) was 5.6 mg kg^{-1} greater than the average Fe concentration of the control treatment (58.9 mg kg^{-1}), suggesting that $FeSO_4{\cdot}7H_2O$ may be effective in providing Fe to corn in problematic areas of these fields (data not shown). Other results from tissue sampling did not provide any additional evidence for identifying a successful treatment to Fe deficiency in corn; consequently, the yield results must be the primary measure of success.

Iron deficiency depends on several factors that cannot be consistently isolated. For instance, environmental conditions are very important in determining the severity of Fe deficiency. High soil moisture content early in the spring will increase the partial pressure of CO_2, which will increase the HCO_3^- concentration in soil solution (Loeppert, 1986). The effect of high soil moisture is similar to what is observed when $CaCO_3$ is present as previously discussed. Detecting a consistent treatment response is difficult because factors affecting Fe deficiency are frequently variable from location to location and from year to year. However, using the grain yield response to $FeSO_4{\cdot}H_2O$ application, a simple economic evaluation based on the data collected from this study is possible. Based on bare soil photographs and yield maps before 1999, average grain yield for Fe-deficient areas was about 10 to 20% of that obtained from the rest of the field for the four study sites in 2000. Problematic areas were related to the presence of high soil $CaCO_3$, which was visually evident from bare soil photographs. Yield maps confirmed that yield was less in those areas with high $CaCO_3$ content. Assuming a yield increase of 0.8 Mg ha^{-1} (Fig. 1) by effectively targeting 81 kg ha^{-1} $FeSO_4{\cdot}H_2O$ to 15% of the field that is problematic, a per-hectare return can be estimated. Assuming fertilizer costs of \$0.53 kg^{-1} (\$42.93 ha^{-1} for the 81 kg ha^{-1} treatment) and only 15% of the field receiving fertilizer, total application cost would be \$6.44 ha^{-1}. Assuming corn prices equal to \$78.67 Mg^{-1}, a 0.8 Mg ha^{-1} yield response on 15% of the field would increase returns by \$9.44 ha^{-1}. This translates into a net return equal to \$3.00 ha^{-1}, which constitutes the most, in this example, that could be spent on precision-farming technologies to implement targeted applications of $FeSO_4{\cdot}H_2O$. Precision-farming cost could be minimal because the necessary equipment to implement this strategy would consist of a global positioning system (GPS) receiver, a controller, and application boxes on the planter. The cost of obtaining the aerial photographs would be small, and application maps would remain unchanged from year to year.

If problematic areas responsive to the addition of $FeSO_4{\cdot}H_2O$ could be successfully identified, the economic return could be even greater. Consider the 1.6 Mg ha^{-1} increase in grain yield that was observed from the addition of 81 kg ha^{-1} $FeSO_4{\cdot}H_2O$ at the four sites for which a positive increase in grain yield was observed (Fig. 2). Assuming that 15% of the field receives $FeSO_4{\cdot}H_2O$ fertilizer and this level of response was observed, the increase in gross return would be \$18.89 ha^{-1}, which translates into a net return equal to \$12.45 ha^{-1}. If the treatment is targeted to problematic areas within a field with the same success as observed at the four responsive sites, this return would be sufficient for many producers to quickly recover the costs of additional equipment for site-specific management.

SUMMARY

With every additional kilogram per hectare of $FeSO_4{\cdot}H_2O$ applied, corn grain yield increased 0.01 Mg ha^{-1} when averaged across all seven site-years. For the 81 kg ha^{-1} $FeSO_4{\cdot}H_2O$ treatment, this corresponded to a 0.8 Mg ha^{-1} grain yield increase compared with the control. Considering only the responsive sites, average grain yield increased 1.6 Mg ha^{-1} with the addition of 81 kg ha^{-1} $FeSO_4{\cdot}H_2O$ (four out of seven site-years). Grain yield responses from the addition of $FeSO_4{\cdot}H_2O$ were inconsistent, and soil characteristics that distinguished responsive and nonresponsive sites were difficult to identify. However, DTPA-extractable Fe levels were below adequate (<4.5 mg kg^{-1}), and soil $CaCO_3$ content was relatively high (>6.5 g kg^{-1}) at every site, indicators that Fe availability may be less than adequate.

Based on the average grain yield response observed at all sites, the addition of $FeSO_4 \cdot H_2O$ could be economically feasible for correcting Fe deficiency in irrigated corn in the Great Plains. Assuming 15% of a field is problematic, potential return would be \$3.00 ha^{-1} if grain yield were increased 0.8 Mg ha^{-1} with the addition of 81 kg ha^{-1} $FeSO_4 \cdot H_2O$. In the past, applying Fe fertilizer to entire fields has not been economically feasible, but with precision-farming technologies, applications of $FeSO_4 \cdot H_2O$ could be targeted only to those areas of the field that are problematic.

REFERENCES

Cihacek, L.J. 1984. Economic soil treatment of iron chlorosis in grain sorghum on a gypsum affected soil. J. Plant Nutr. 7:329–340.

Dofing, S.M., E.J. Penas, and J.W. Maranville. 1989. Effect of bicarbonate on iron reduction by soybean roots. J. Plant Nutr. 12: 797–802.

Frank, K., D. Beegle, and J. Denning. 1998. Phosphorus. p. 21–29. *In* Ellis et al. (ed.) Recommended chemical soil test procedures for the North Central Region. North Central Regional Res. Publ. 221 (revised). Missouri Agric. Exp. Stn. SB 1001, Columbia.

Geiseking, J.E., H.J. Snider, and C.A. Getz. 1935. Destruction of organic matter in plant material by the use of nitric and perchloric acids. Ind. Eng. Chem. Anal. Ed. 7:185–186.

Hergert, G.W., P.T. Nordquist, J.L. Petersen, and B.A. Skates. 1996. Fertilizer and crop management practices for improving maize yields on high pH soils. J. Plant Nutr. 19:1223–1233.

Lindsay, W.L. 1984. Soil and plant relationships associated with iron deficiency with emphasis on nutrient interactions. J. Plant Nutr. 7:489–500.

Loeppert, R.H. 1986. Reactions of iron and carbonates in calcareous soils. J. Plant Nutr. 9:195–214.

Loeppert, R.H., L.C. Wei, and W.R. Ocumpaugh. 1994. Soil factors influencing mobilization of trace metals in calcareous soils. p. 345–363. *In* J.A. Manthey, D.E. Crowley, and D.G. Luster (ed.) Biochemistry of metal micronutrients in the rhizosphere. Lewis Publ., Boca Raton, FL.

Mathers, A.C. 1970. Effect of ferrous sulfate and sulfuric acid on grain sorghum yields. Agron. J. 62:555–556.

Mortvedt, J.J., and P.M. Giordano. 1970. Crop response to iron sulfate applied with fluid polyphosphate fertilizers. Fert. Solutions 14(4): 22–27.

Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. p. 961–1010. *In* Weaver et al. (ed.). Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA and ASA, Madison, WI.

Olson, R.V. 1950. Effects of acidification, iron oxide addition, and other soil treatments on sorghum chlorosis and iron absorption. Soil Sci. Soc. Am. Proc. 15:97–101.

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1989. How a corn plant develops. Spec. Rep. 48. Iowa State Coop. Ext., Iowa State Univ., Ames.

Römheld, V., and H. Marschner. 1986a. Evidence for specific uptake system for iron phytosiderophores in roots of grasses. Plant Physiol. 80:175–180.

Römheld, V., and H. Marschner. 1986b. Mobilization of iron in the rhizosphere of different plant species. Adv. Plant Nutr. 2:155–204.

Römheld, V., H. Marschner, and D. Kramer. 1982. Response to Fe deficiency in roots of "Fe-inefficient" plant species. J. Plant Nutr. 5:488–498.

SAS Institute. 1998. SAS/STAT user's guide. Release 6.03. SAS Inst., Cary, NC.

Soil Survey Staff. 1961. USDA Soil Conservation Service, Soil Survey-Stevens County, Kansas. Series 1958, No. 13. U.S. Gov. Print. Office, Washington, DC.

Soil Survey Staff. 1965a. USDA Soil Conservation Service, Soil Survey- Finney County, Kansas. Series 1961, No. 30. U.S. Gov. Print. Office, Washington, DC.

Soil Survey Staff. 1965b. Soil Survey—Scott County, Kansas. USDA-SCS Ser. 1961, No. 33. U.S. Gov. Print. Office, Washington, DC.

Steel, R.G., and J.H. Torrie. 1980. Principals and procedures of statistics: A biometrical approach. 2nd ed. McGraw-Hill, New York.

Thomas, J.D., and A.C. Mathers. 1979. Manure and iron effects on sorghum growth on iron-deficient soil. Agron. J. 71:792–794.

Vempati, R.K., and R.H. Loeppert. 1986. Synthetic ferrihydrite as a potential iron amendment in calcareous soils. J. Plant Nutr. 9: 1039–1052.

Vempati, R.K., and R.H. Loeppert. 1988. Chemistry and mineralogy of Fe-containing oxides and layer silicates in relation to plant available iron. J. Plant Nutr. 11:1557–1574.

Wallace, A., R.T. Mueller, P.M. Patel, and S.M. Soufi. 1976. Use of waste pyrites from mine operations on highly calcareous soil. Commun. Soil Sci. Plant Anal. 7:57–60.

Warncke, D., and J.R. Brown. 1998. Potassium and other basic cations. p. 31–33. *In* Ellis et al. (ed.) Recommended chemical soil test procedures for the North Central Region. North Central Regional Res. Publ. 221 (revised). Missouri Agric. Exp. Stn. SB 1001, Columbia.

Whitney, D.A. 1983. Soil test interpretations and fertilizer recommendations. Bull. C-509. Kansas State Univ. Coop. Ext. Serv., Manhattan, KS.

Whitney, D.A. 1998. Micronutrients: Zinc, iron, manganese and copper. p. 41–44. *In* Ellis et al. (ed.) Recommended chemical soil test procedures for the North Central Region. North Central Regional Res. Publ. 221 (revised). Missouri Agric. Exp. Stn. SB 1001, Columbia.