SITE-SPECIFIC MANAGEMENT OF IRON DEFICIENCY IN CORN

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The addition of $FeSO_4 \cdot H_2O$ in the seed row increases corn (*Zea mays* L.) yield in areas with Fe deficiency-induced chlorosis. Our objectives were to determine the correct application rate of $FeSO_4 \cdot H_2O$ for irrigated corn, identify the spatial distribution of Fe deficiency, and alleviate deficiency symptoms with targeted $FeSO_4 \cdot H_2O$ applications. Eleven site-years were selected for small-plot studies in western Kansas. At these fields, soil $CaCO_3$ content in chlorotic or problematic deficient areas of the field ranged from 0.4 to 21.1%. Bare soil photographs, soil test analysis, and yield maps from previous years were used to identify possible Fe deficient areas. Bare soil reflectance was related to soil $CaCO_3$ content, which was related to DTPA-Fe. In 2000 and 2001, 81 kg ha^{-1} $FeSO_4 \cdot H_2O$ was applied to 18-m to 36-m wide strips in three fields to evaluate the potential for targeting applications to identified areas exhibiting Fe deficiency. During 1999 and 2000, grain yield increased linearly with increasing $FeSO_4 \cdot H_2O$ at four of seven site years (small plots), increasing 0.02 Mg ha^{-1} per kg ha^{-1} $FeSO_4 \cdot H_2O$. Grain yield increased 0.7 Mg ha^{-1} at one of three whole-field sites in 2000. Improving the probability of response will be important to improving the economic return to the treatment and costs associated with precision farming technologies. The use of precision farming technologies appears to provide a practical solution to the spatial variability of Fe deficiency in irrigated corn.

Methods and Materials

Field studies were conducted at five locations in southwestern Kansas in 1999 and 2000 (seven-site years total). Soils at these sites developed from silty to sandy sediments or windblown material. Corn was grown every year at these sites. The Finney Co. site was flood irrigated and all other sites were center-pivot irrigated. Pioneer hybrid 3489 was planted at a seed density of 75,582 ha^{-1}. All N, P, and K fertilizer, water, and herbicide scheduling was determined by individual producers and were typical for this area.

Bare soil photographs were taken in the spring of 1999 to help identify the spatial distribution of problematic areas. Resolution of the photographs was approximately 1-m. Handling and manipulation of the photographs was done with Arcview (Environmental Systems Research Institute, Inc., Redlands, CA).

Small plot sites were soil sampled both years. Soil samples were collected prior to planting each year from each small-plot location and 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), 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 percent C as $CaCO_3$.

In 2000, $FeSO_4 \cdot H_2O$ was applied to strips in three separate fields at a rate of 81 kg product ha^{-1}. Application strips were positioned to intersect a known chlorotic area in the field (Figure 1). Iron sulfate monohydrate was applied with Gandy PDM™ fertilizer boxes mounted on a 12-row planter. The $FeSO_4{\bullet}H_2O$ was placed directly in the seed row by running a hose from the Gandy box directly in front of the press wheels on the planter. Soil samples were collected along the Fe application strip in 2000. Ten sample cores (2.5-cm i.d.) were obtained from a depth of 0 to 20-cm within a 3- m radius around the sample point.

Small plot grain yield was determined in 1999 by hand harvesting 12-m length of row, while in 2000 grain yield was determined by harvesting the full length of the middle two rows with a Gleaner E combine modified for plot work. Yield data from the whole field from 1997-2000 was measured on 1-s interval with a Greenstar™ yield mapping system on a John Deere 9750 with a 12-row corn head (John Deere Company, Moline, Illinois). Yield data was then compiled and exported from the yield monitors to a common text format. This data was then imported into ArcView software (Environmental Systems Research Institute, Inc., Redlands, CA).

Results

Small Plot Studies

Soil characteristics at all small plot sites were typical of soils that are conducive to Fe deficiency in corn. 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 ranged from 2 to 4 mg kg^{-1}. 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}. The presence of $CaCO_3$ adversely affects natural occurring Fe uptake mechanisms, thus causing a higher HCO_3^- concentration in the soil solution relative to $CaCO_3$ free soils (Loeppert et al., 1994). Olsen P levels ranged from 6 to 33 mg kg^{-1}. Soil characteristics associated with these sites were similar to those from other Fe fertility research for irrigated corn on the Great Plains (Hergert et al., 1996).

A significant difference in 1999 and 2000 among treatments was detected for grain yield when data from all seven site years was combined; however, when data from either year was evaluated individually, there was not a significant difference among treatments. Because the general F test does not provide an evaluation of specific trends (Steel and Torrie, 1980) contrasts were used to determine differences for planned comparisons of specific treatments or combinations of specific treatments at individual sites and across all site years. A contrast was considered significant when Prob.>F was less than or equal to 0.10.

The most consistent treatment response that was detected from individual sites was the linear increase in grain yield due to the addition of $FeSO_4{\bullet}H_2O$ (Table 1). In 1999 at sites SE14 and Finney, grain yield increased linearly with increasing rates of $FeSO_4{\bullet}H_2O$. Grain yield at SE14 ($y=0.02+11.3$) increased 0.02 Mg ha^{-1} for every 1 kg ha^{-1} $FeSO_4{\bullet}H_2O$ added. While at Finney ($y=0.01x+9.7$), grain yield increased 0.01 Mg ha^{-1} for every additional 1 kg ha^{-1} $FeSO_4{\bullet}H_2O$. In 2000 at individual sites, the addition of $FeSO_4{\bullet}H_2O$ significantly increased grain yield linearly at NW33 ($y=0.02+7.6$). Grain yield at NW33 increased 0.02 Mg ha^{-1} with each additional increment (kg ha^{-1}) of $FeSO_4{\bullet}H_2O$. The other notable linear response to the addition of $FeSO_4{\bullet}H_2O$ was at SW29 ($y=0.02x+9.7$) in 2000, although the Prob.>F for this linear contrast was only 0.12. Including the SW29 results, grain yield was significantly affected by $FeSO_4 \cdot H_2O$ at four of seven sites.

Identifying Problematic Areas

Problematic areas associated with Fe deficiency were identified in a three-step process. These areas represented soils with $CaCO_3$ greater than 40 mg kg^{-1} and historical yield that was relatively smaller than the field average yield. 1) The area had to be contiguous and large enough to allow an evaluation of yield with a combine equipped with a yield monitoring system (e.g., > 2 combine header widths wide and > 60 m long). 2) Yield maps from 1997 and 1998 were used to identify low yielding areas. 3) Bare soil photographs were used to identify lighter colored areas that were expected to correspond with greater soil $CaCO_3$ content.

Reflectance and $CaCO_3$ content in application strips at SE14 and NW33 were related (Figure 2). However, at SW29 the relationship observed was different. This is probably due to the spatial variability in soil texture at SW29 when compared to the other two sites. Sand content in the soil at SW29 was greater than the other two sites and this probably influenced the amount of reflected light. Another soil property that is associated with sandy soils is lower organic matter content. Low organic matter soils tend to reflect more light compared to high organic matter soil which have a darker color. Using bare soil photographs in conjunction with previous years yield map and soil samples provided a good way of identifying the problematic areas of the field that may be associated with Fe deficiency.

A relationship between DTPA-Fe levels and soil $CaCO_3$ content for all the samples collected from the transects at SE14, NW33, and SW29 indicated that DTPA-Fe decreased exponentially with increasing soil $CaCO_3$ content (Figure 3). Based on this relationship when soil $CaCO_3$ content was above 6.5 g kg^{-1}, DTPA-extractable Fe was below 4.5 mg kg^{-1}. As previously mentioned, Fe deficiency is usually related to areas of high soil $CaCO_3$ content. At these three sites, high soil $CaCO_3$ content coincided with lower DTPA-Fe levels.

Field Scale Study

Grain yield from 1997, 1998, and 1999 were used as a basis for evaluating grain yield response to the addition of 81 kg ha^{-1} $FeSO_4 \cdot H_2O$ in 2000. Yield monitor data from each year were averaged for individual 18.2 m x 18.2 m grid cells for the length of the Fe application strip. Observations were separated into those within the problematic area and those outside the problematic area. Yield data from inside the application strip were compared to data from areas adjacent to, but outside, the application strip. T tests were used to determine if yield inside the Fe application strip was similar to yield outside the application strip, for the problematic area and outside the problematic area.

Prior to 2000 (1997–1999) when 81 kg ha^{-1} $FeSO_4 \cdot H_2O$ was applied for the first time, grain yield in the problematic area of SE14, but outside the Fe application strip (No Fe), was consistently greater than grain yield inside the application strip (Fe) (Table 2). Yield potential appears to be greater outside the application strip. In 2000, grain yields in the problematic area were similar for the Fe and No Fe treatments (Table 2). Because grain yield from 1997-1999 indicated that yield potential was greater outside the applications strip (No Fe treatment in 2000), an evaluation of the 81 kg ha^{-1} $FeSO_4 \cdot H_2O$ treatment should account for these yield potential differences. Grain yield in 2000 was subtracted from average grain yield from 1997-1999. Yield difference for the Fe treatment, -1.8 Mg ha^{-1}, was greater than the difference for the No Fe treatment, -2.6 Mg ha^{-1}. Although overall yield was less in 2000, 0.7 Mg ha^{-1} greater yield could be attributed to the addition of 81 kg ha^{-1} $FeSO_4 \cdot H_2O$ (Table 2). The below normal precipitation in Stevens County Kansas during May, June, and July 2000 may have limited potential grain yields at SE14. Whole-field average grain yield at SE14 was 1.7 Mg ha^{-1} less in 2000 than the average yield from the three previous years. Significant differences were not detected outside the problematic spot at any of the sites. Outside the problematic area usually corresponded to areas with DTPA-extractable Fe levels in the soil greater than 4.5, which is above the critical threshold (Whitney, 1983). Soil $CaCO_3$ levels were less than 6.5 g kg^{-1} outside the problematic area.

Soil $CaCO_3$ was greater than 8 mg kg^{-1} and DTPA Fe was less than 4 mg kg^{-1}throughout most of the application strips at NW33 and SW29. This indicates that the addition of $FeSO_4 \cdot H_2O$ may still be beneficial, although yield response was not observed using this yield monitor approach. Because of the within-field variability in yield-limiting soil characteristics, e.g. sand content and depth of $CaCO_3$, an unreplicated strip trial may not be the best tool for evaluating yield responses. For this reason in 2001 a replicated strip trial was used where numerous problematic areas were targeted for $FeSO_4 \cdot H_2O$ application strips. Grain yield was increased significantly with the addition $FeSO_4 \cdot H_2O$ at one out of three Fe application strip sites in 2000. A grain yield response to the addition of $FeSO_4 \cdot H_2O$ was observed at four out of seven small plot sites in 1999 and 2000. With additional site years in 2001, for the application strips, the same probability of response as the one observed with the small plot study might be observed with the strip trials.

Summary

With every additional 1 kg ha^{-1} $FeSO_4 \cdot H_2O$ applied grain yield increased 0.01 Mg ha^{-1}, when averaged across seven site years. For 81 kg ha^{-1} $FeSO_4 \cdot H_2O$, this corresponded to a 0.8 Mg ha^{-1} grain yield increase compared to the control. Grain yield increased 1.6 Mg ha^{-1} with the addition of 81 kg ha^{-1} $FeSO_4 \cdot H_2O$, based on the linear response observed at four out of seven sites years. Soil sample transects through three fields indicated that problematic areas were associated with levels of DTPA-extractable Fe below 4.5 mg kg^{-1} and soil $CaCO_3$ content levels greater than 6.5 g kg^{-1}. The presence of soil $CaCO_3$ could potentially be used to identify problematic areas because these areas can be identified visually or with remote sensing.

The grain yield response observed in the Fe application strips was similar to the response observed at small plot locations. The addition of 81 kg ha^{-1} $FeSO_4 \cdot H_2O$ increased grain yield by 0.7 Mg ha^{-1} inside the problematic area in the Fe application strip at one field when compared to grain yield from the No Fe treatment. This was observed for only one out of three sites. With additional site years for the application strips, a similar response, to the one observed at the small plot sites, might be observed.

Grain yield response observed at small plot sites indicated that targeting applications of $FeSO_4 \cdot H_2O$ to problematic areas within a field might be economically feasible. If problematic areas responsive to the addition of $FeSO_4 \cdot H_2O$ could be successfully distinguished from those

sites that are non-responsive, the economic return would be even greater. Site-specific applications of $FeSO_4 \cdot H_2O$ to problematic areas within a field appear to be an effective way to alleviate economic loss sustained from Fe deficiency induced chlorosis in corn.

Table 1. Average corn grain yield from small plot studies in 1999 and 2000.

		Treatments							
		$FeSO_4 \bullet H_2O$ (kg ha^{-1})							
Year	Site	0	27	54	81	Foliar	$CaSO_4 \bullet 2H_2O$	$FeSO_4 \bullet 7H_2O$	S.E.¶
		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
	Average	10.9	11.8	11.4	12.1	11.3	na	na	0.33
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	9.0	9.2	9.3	9.7	8.9	9.0	9.5	0.36
	Average‡	9.8	10.3	10.2	10.7	9.9	10.0§	10.5§	

† The liquid $FeSO_4 \bullet 7H_2O$ and $CaSO_4$ 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® Institute Inc., 1998).
¶ Standard error

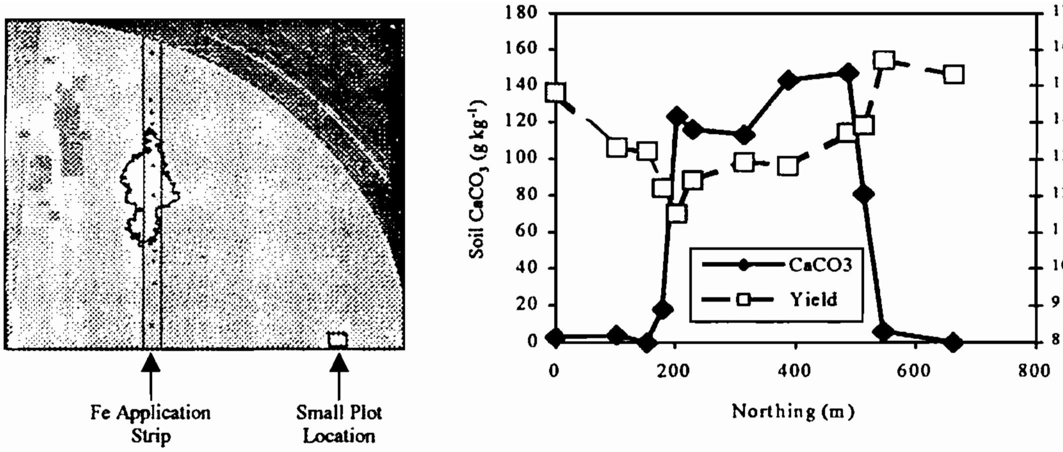

Figure 1. Soil $CaCO_3$ content and grain yield (1999, without treatment) at each soil sample point (closed circles) in the SE14 Fe application strip. Zero northing corresponds to the soil sample point at the bottom of the field. Problematic area is outlined. Yield was determined by averaging yield data points (from yield monitor) that were within 7.6 m of the sample point.

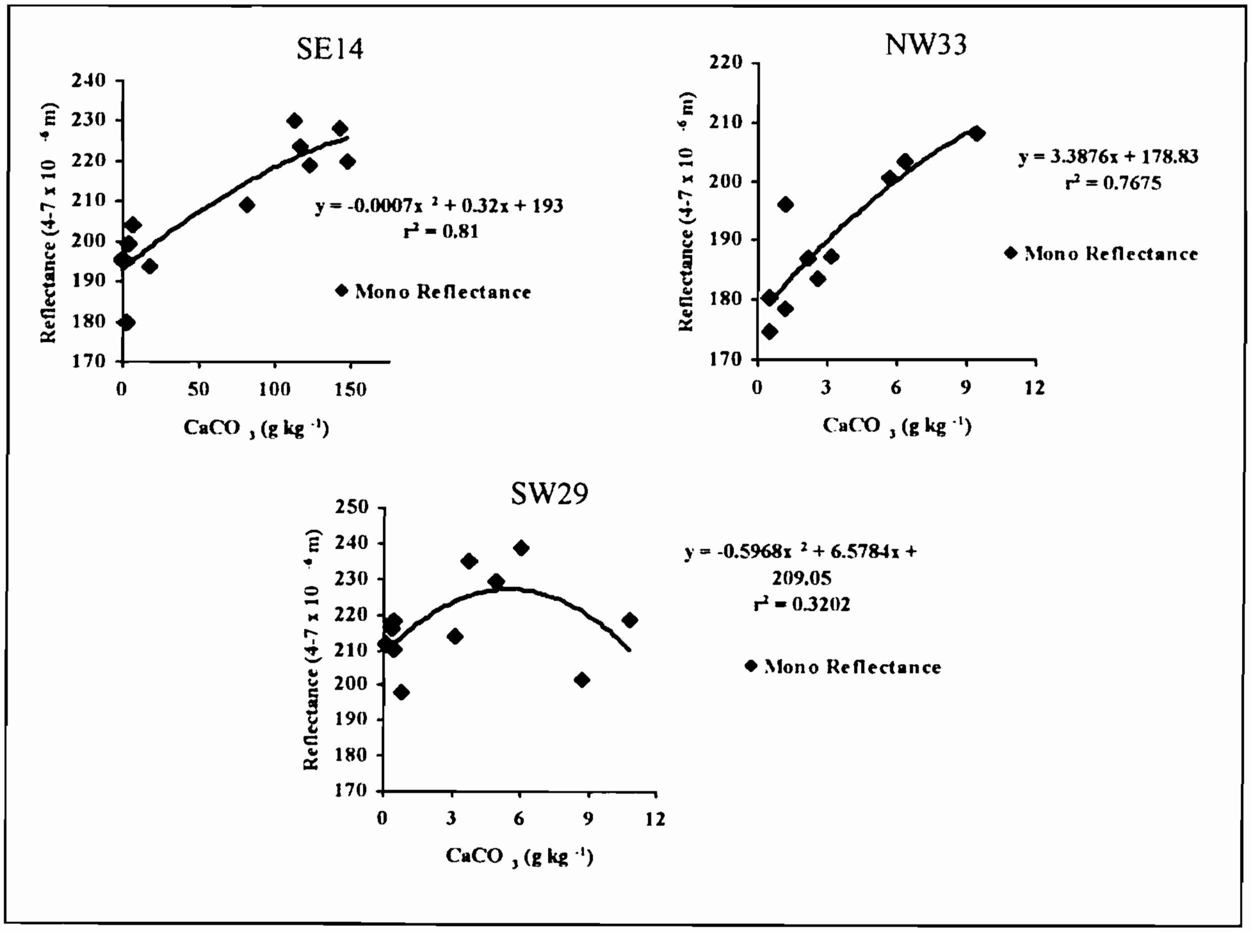

Figure 2. Monotone reflectance as a function of soil $CaCO_3$ for soil sample points in the SE14, NW33, and SW29 Fe application strip. Reflectance was determined by averaging the pixel values in the bare soil photograph that were within 3 m of the sample point. The wavelength of the mono reflectance is $4 - 7 \times 10^{-6}$ m.

Table 2. Grain yield comparisons† from Fe application strips in 1997, 1998, 1999 and 2000 at SE14, using average grain yield from yield monitor data.

Location	Year	Yield		Pr > T
		Fe	No Fe	
		--- Mg ha^{-1} ---		
Problematic Area‡		(n = 26)§	(n = 23)	
	1997	13.2	13.5	0.13
	1998	11.7	12.3	0.01
	1999	12.8	13.4	0.01
	Average	12.6	13.1	
	2000	10.7	10.5	0.20
	Difference¶	-1.8	-2.6	0.01
Outside Area		(n = 35)	(n = 35)	
	1997	13.0	13.2	0.71
	1998	13.9	13.8	0.79
	1999	14.0	14.1	0.77
	Average	13.6	13.7	
	2000	12.4	12.5	0.53

† Comparing yield inside the application strip to adjacent areas immediately outside the application strip. "Fe" area did not receive Fe application prior to 2000.
‡ Problematic area (Fe deficient) as defined in material and methods.
§ Number of observations (18 x 18 m cells) for treatment.
¶ Represents 2000 yield – Average yield (1997-1999).

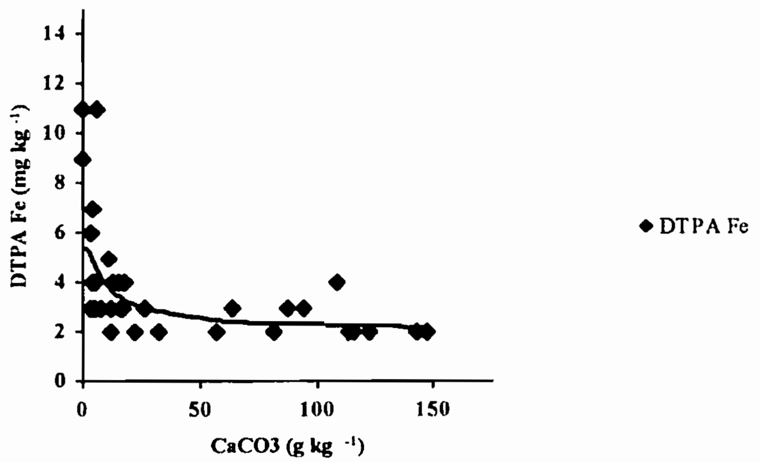

Figure 3. DTPA Fe as a function of soil $CaCO_3$ content for soil sample points in the NW33, SW29, and SE14 Fe application strip.

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