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Soybean

Soybean Iron-Deficiency Chlorosis Tolerance and Yield Decrease on Calcareous Soils

T. C. Helms,* R. A. Scott, W. T. Schapaugh, R. J. Goos, D. W. Franzen, and A. J. Schlegel

ABSTRACT

Cultivar selection is one of the best ways to manage iron-deficiency chlorosis (IDC) problems in soybean [*Glycine max* (L.) Merr.]. The objective was to determine if precision farming techniques of planting IDC-tolerant cultivars in calcareous soil areas and high-yielding cultivars in non-IDC areas would increase soybean yield. We used paired sites within the same field. The sites were located in areas of a field where IDC was present and absent. The same commercial soybean cultivars were planted on the paired sites. Results showed that visual scores for IDC could not identify the highest-yielding cultivar in IDC-affected areas. If the only information available to growers is yield on non-IDC sites and visual IDC ratings, then the yield of the whole field could be increased by planting two different cultivars. If yield data from replicated performance testing of numerous different cultiars was available for IDC sites and also for non-IDC sites, then growers may be able to identify a single cultivar that has high yield across the entire field.

Iron-deficiency chlorosis reduces yield of soybean. Many fields show IDC symptoms on only part of the field area. There are genetic differences among cultivars for yield on the non-IDC portion of a field and also in tolerance to IDC. Yield of the whole field might be maximized by planting the highest-yielding cultivar on that part of the field where IDC is absent and planting an IDC-tolerant cultivar where IDC is present. This research was designed to determine whether a single cultivar will maximize yield for a field that has IDC areas and non-IDC areas.

Niebur and Fehr (1981) evaluated 19 experimental soybean lines, which were tolerant to IDC, on both calcareous and noncalcareous soil. When they applied a postemergence iron chelate on the soybean genotypes grown on the calcareous soil at each site, they found no genotype × soil type interaction for yield between the calcareous and noncalcareous soils. Based on these results, they concluded that IDC-tolerant genotypes could be evaluated for yield on either calcareous or noncalcareous soil types. Goos and Johnson (2000) reported that selection of an IDC-tolerant cultivar was critical to increasing yields on calcareous soils.

Froehlich and Fehr (1981) reported that yield decreased 20% for each one unit increase in IDC score (1 = best, 5 = worst) and that IDC score could be used as a reliable predictor of yield on the calcareous areas of a field. Naeve and Rehm (2006) reported that as visual IDC symptoms increased, there was an associated decrease in yield, but that screening of cultivars for IDC tolerance should also include yield evaluation on sites where IDC is present.

Previous research (Franzen and Richardson, 2000; Hansen et al., 2003) has shown that soluble salts, calcium carbonate equivalent (CCE), soil pH, and soil Fe cannot be used as reliable predictors for identifying areas where IDC will reduce soybean yields. Hansen et al. (2003) had similar results and concluded that soil pH and CCE were not a reliable predictor of which portions of field would be the most susceptible to IDC.

In many fields, IDC problems can be reduced by planting tolerant cultivars. However, planting an IDC-tolerant cultivar may be more cosmetic because visual IDC symptoms are reduced, but yield of the entire field may not be maximized. Our objective was to determine whether a precision farming technique of planting IDC-tolerant cultivars in problem areas and high-yielding cultivars in non-IDC areas would increase soybean yield.

MATERIALS AND METHODS

A total of five environments were evaluated in North Dakota and South Dakota. Four environments were evaluated in Kansas. In North Dakota and South Dakota, 18 Maturity Group 0 soybean cultivars were evaluated on paired sites, within the same fields. In Kansas, 20 soybean cultivars of Maturity Group III and early Maturity Group IV were evaluated on paired sites within the same fields. Yield was evaluated for each cultivar on each of the paired sites. All IDC sites had a past history of iron chlorosis. Cultivars were glyphosate [N-(phosphonomethyl) glycine]-resistant.

The experimental design for individual trials (IDC and non-IDC), which we will refer to as sites within an environment,

T.C. Helms, Dep. of Plant Sciences, NDSU Dep. 7670, P.O. Box 6050, and R.J. Goos and D.W. Franzen, Dep. of Soil Science, NDSU Dep. 7680, P.O. Box 6050, Fargo, ND 58108; R.A. Scott, USDA-ARS, 5601 Sunnyside Ave., GWCC 4-2218, Beltsville, MD 20705-5139; W.T. Schapaugh, Dep. of Agronomy, Kansas State Univ., Manhattan, KS 66506; A.J. Schlegel, Southwest Research Extension Center, Kansas State Univ., Tribune, KS 67879. Received 20 Aug. 2009. *Corresponding author (ted.helms@ndsu.edu).

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Abbreviations: IDC, iron-deficiency chlorosis; CCE, calcium carbonate equivalent; SCN, soybean cyst nematode.

was a randomized complete block with three replicates. The treatments assigned to each experimental unit were the different cultivars that were evaluated. For the statistical analysis, sites were nested within environments.

The border rows of each site within each North Dakota, South Dakota, and Kansas environment, included the same two common check cultivars across all three states. One border row of each site consisted of a cultivar that was sensitive to IDC and a second border row of each site consisted of cultivar that was known to be tolerant to IDC. The maturity of these cultivars planted to the border rows was Maturity Group II. The purpose of using the same two cultivars for North Dakota, South Dakota, and Kansas border rows was to have a way of comparing the level of IDC across sites that included different states. The purpose of using visual IDC ratings of the same IDC-sensitive cultivar assigned to border rows was to measure and confirm the differences in IDC symptoms between the IDC site and non-IDC site within and across environments. The same person rated the IDC and non-IDC sites within each environment.

Visual IDC ratings were taken on border rows of each site and on yield-trail plots of each site. For the 20 cultivars evaluated in Kansas, visual ratings for IDC were only taken on yield-trial plots, but there were no hill-plot ratings taken for these cultivars.

When yield is regressed on the hill-plot ratings, there is no environmental covariance between yield (dependent variable) and visual IDC rating (independent variable). This is because the yield-plot and the hill-plot do not share a common plot (Casler, 1982). As IDC symptoms measured on yield-trial plots become more severe, yield is expected to decrease due to a environmental covariance between the dependent variable and the independent variable. Our purpose in regression of yield on IDC visual rating was to evaluate a genetic relationship between IDC visual ratings and yield. Regression of yield on the hill-plot visual IDC rating measured the genetic relationship between these two traits without the confounding effects of a shared environment. The regression of yield on visual IDC ratings, based on the Kansas data, confounds the genetic differences among cultivars with the effect of the environmental influence on that relationship.

Iron-deficiency chlorosis was rated at the V2–V3 trifoliolate stage and the second time at the V5–V6 trifoliolate leaf stage (Fehr and Caviness, 1977). In this scale, a rating of 1 represented no chlorosis, 2 represented a slight yellowing of the upper leaves of a general (not interveinal) nature, 3 represented interveinal chlorosis of the upper leaves without stunting or necrosis, 4 represented interveinal chlorosis of the upper leaves with reduced growth or the beginning of necrosis, and 5 represented severe stunting, chlorosis, and damage to the growing point. Visual IDC ratings were recorded to the nearest one-half unit (±0.5) for each rating for each yield-trail plot and each hill-plot.

North Dakota and South Dakota

The 18 cultivars tested in North Dakota and South Dakota sites were relabeled Dakota-1 through Dakota-18 in this manuscript. Twenty soil samples collected from the 0- to 0.15-m depth at each site were evaluated for soybean cyst nematode infestation, P, K, pH, electrical conductivity, CCE, and nitrate nitrogen (Table 1). Soil analysis for all years and states was conducted at the North Dakota State University soil testing laboratory.

The soil type at the 2007 Hunter, ND, IDC site was an Embden coarse-loamy, mixed, superactive, frigid Pachic Hapludolls, and on the non-IDC site the soil was a Fordville fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Pachic Hapludolls. The soil type at the 2007 Galchutt, ND, IDC site was a Glyndon loam, coarse-silty, mixed, superactive, frigid Aeric Calciaquolls-Wyndmere loam, coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls complex, and at the non-IDC site it was a Glyndon loam. The soil type at the 2007 Arthur, ND, site (IDC and non-IDC) was a Glyndon loam. The soil type at the 2006 Brookings, SD, location was a Divide loam, fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Aeric Calciaquolls, and at the 2007 Brookings, SD, location it was a Lowe loam, fine-loamy, mixed, super-

Table 1. Soybean cyst nematode (SCN) egg count, phosphorus, potassium, pH, electrical conductivity (EC), calcium carbonate equivalent (CCE), and nitrate nitrogen for iron-deficiency chlorosis (IDC) and non-IDC paired sites for each testing environment.

Environment	Site	SCN	P	K	pH	EC	CCE	NO_3–N
		eggs 100 cc^{-1}	mg kg^{-1}			mmhos cm^{-1}	%	mg kg^{-1}
Arthur, ND, 2006	IDC	13	17,000	102,000	8.4	0.4	3.7	9,300
Arthur, ND, 2006	non-IDC	0	12,000	83,000	7.9	0.3	0.7	6,200
Brookings, SD, 2006	IDC	0	11,000	90,000	8.3	0.3	6.2	7,500
Brookings, SD, 2006	non-IDC	50	12,000	117,000	8.3	0.3	7.7	152,000
Hunter, ND, 2007	IDC	0	7,000	45,000	8.5	0.3	9.7	5,000
Hunter, ND, 2007	non-IDC	0	45,000	290,000	6.6	0.2	0.5	8,000
Galchutt, ND, 2007	IDC	0	2,000	40,000	8.6	0.4	5.3	5,000
Galchutt, ND, 2007	non-IDC	300	3,000	30,000	7.6	0.2	0.6	5,000
Brookings, SD, 2007	IDC	0	14,000	75,000	8.3	0.3	6.9	13,000
Brookings, SD, 2007	non-IDC	0	95,000	335,000	7.7	0.6	0.4	12,000
Tribune, KS, 2006	IDC	0	6,000	505,000	7.8	0.6	2.8	66,000
Tribune, KS, 2006	non-IDC	0	11,000	665,000	7.7	0.5	1.1	45,000
Zeandale, KS, 2006	IDC	13	6,000	181,000	8.1	0.3	5.7	20,000
Zeandale, KS, 2006	non-IDC	13	4,000	272,000	7.9	0.2	1.7	17,000
Tribune, KS, 2007	IDC	38	5,000	440,000	7.8	0.5	3.3	13,000
Tribune, KS, 2007	non-IDC	0	14,000	650,000	7.7	0.7	0.3	30,000
Zeandale, KS, 2007	IDC	75	6,000	330,000	7.4	0.5	0.8	2,000
Zeandale, KS, 2007	non-IDC	0	12,000	310,000	7.3	0.4	0.5	4,000

Table 2. Analyses of variance for yield of soybean cultivars evaluated at paired iron-deficiency chlorosis (IDC) and non-IDC sites at five environments in North and South Dakota, and at four environments in Kansas. Yield was not adjusted for maturity in these analyses.

Sources of variation	North and South Dakota df	North and South Dakota Mean squares	Kansas df	Kansas Mean squares
Environment	4	26,159,970**	3	21,436,070**
Site (Environment)	5	13,312,900**	4	56,222,630**
Block (Site × Environment)	20	827,050**	16	656,500**
Cultivar	17	1,393,700**	19	801,570
Environment × Cultivar	68	290,570**	57	593,500**
Environment × Site × Cultivar	85	342,110**	76	455,760**
Residual	340	115,190	304	263,180

** Significant at the 0.05 probability level.

active, frigid Typic Calciaquolls-Ludden loam, fine, smectitic, frigid Typic Endoaquerts complex.

Yield was measured by harvesting the middle two rows of the four-row plot. Plots in North Dakota were planted 3.3-m long with 0.76-m between-row spacing. The seeding rate of North Dakota plots was 427,000 seeds ha^{-1}. Plots in South Dakota were 4.2 m long with 0.76-m between-row spacing. The seeding rate in South Dakota plots were 400,000 seeds ha^{-1}. Plots were not end-trimmed. The planted plot length was the same as the harvested plot length.

Visual IDC scores were taken for each of the 18 Maturity Group 0 cultivars, on hill-plots at each of four North Dakota sites in 2007, averaged across three replicates at each site. The areas where IDC-scores were determined using hill-plots, were not the same as harvest areas. Soils at the four hill-plot sites were classified as Aeric Calciaquolls and had a high seasonal water table, and free $CaCO_3$ in the soil surface. The four sites were selected based on a past history of IDC symptoms. The experimental unit consisted of hills planted with eight seeds and thinned to three seeds per hill during the seedling stage. The experimental unit was one hill. Hills were spaced on a 0.76-m grid. Before the regression analysis was conducted, the hill-plot visual IDC ratings were first averaged across replicates, locations, and growth stages. Yield, adjusted for maturity, was then regressed on the IDC hill-plot ratings of each cultivar. Iron-deficiency chlorosis was also rated on yield-trial plots at both the V2–V4 and R2–R3 stages (Fehr and Caviness, 1977) using the same scale that was used for the hill-plot data.

Visual IDC ratings were not taken at the 2007 Brookings, SD site. However, relative leaf chlorophyll concentration were obtained using a Minolta SPAD meter (Minolta, Ramsey, NJ) at the 2007 Brookings, SD site. One random leaf was measured on each of 10 plants within a plot at this site at the V2–V4 and also for the R2–R3 growth stages.

Kansas

The 20 cultivars evaluated in Kansas are identified as Kansas-1 through Kansas-20 in this manuscript. The two locations included Tribune and Zeandale, KS. Yield at all sites were determined by harvesting the middle two row of a four-row plot. Plots at Tribune, KS, were planted to a length of 4.6 m and end-trimmed to a harvest length of 3.7 m. Plots at Zeandale, KS, were planted to a length of 3.4 m and were not end-trimmed. The between-row spacing was 0.76 m and the seeding rate was 342,000 seeds ha^{-1}. The site at Tribune, KS, was irrigated. The site at Zeandale, KS, was not irrigated.

The soil type at Tribune, KS, was a Ulysses silt loam (fine silty, mixed, mesic, Aridic Haplustoll). The soil type at Zeandale, KS, was a Musotah silty clay (fine, smectitic, mesic Aquertic Hapludoll). Iron-deficiency chlorosis was rated twice, once at the V2–V4 vegetative stage and a second time at the R2–R3 reproductive stage.

Statistical Design and Analysis

Cultivars and sites were considered fixed effects. Environments and blocks within each site were considered random effects. The structure of the experiment is shown in Table 2. Mean squares were equated to expected mean squares to determine the proper denominator for F tests. The cultivar source of variation was tested, using the environment × cultivar mean square as the denominator for the F test. Statistical analysis was conducted using PROC ANOVA and PROC GLM (SAS Institute, 2004).

Given a full-length growing season, later-maturing soybean genotypes tend to yield more than early maturing genotypes when cultivars of different maturity are tested at the same environment. To compare the yield of cultivars with different maturities on the IDC and non-IDC areas of the field by regression on visual IDC score (Fig. 1), maturity was first used as a covariate (Miller and Fehr, 1979). The maturity covariate was the date that 95% of the pods reached the mature pod color of brown or gray. The formula used was

$$\mathrm{ADJYLD} = y_i - w(x_i - x),$$

where ADJYLD is the yield adjusted for maturity, y_i is the observed mean yield, x_i is the maturity of the ith line in days from 1 August to 95% mature pod color, x is the mean maturity of all cultivars, and w is the regression coefficient for yield on maturity. Separate regression equations were used to adjust yield for maturity on the IDC and non-IDC sites. The x variable is days from 1 August to maturity.

Regression of yield adjusted for maturity on visual IDC score was conducted to evaluate the overall relationship between these two variables. The adjusted yield for each cultivar was used as the dependent variable and the visual IDC score for each cultivar was used as the independent variable in regressions. One regression equation was developed for the IDC sites and a separate regression equation was developed for the non-IDC sites. These two regression equations were used to evaluate the relationship between visual IDC score and yield (adjusted for maturity) on both IDC and non-IDC portions of fields. The slopes of these two regression equations were compared using a t test (Steel and Torrie, 1960). The North Dakota and South Dakota data was pooled into one combined ANOVA. This was done because the same 18 cultivars were used in both states.

RESULTS AND DISCUSSION

North Dakota and South Dakota

The results of IDC ratings on the susceptible cultivar, which was planted on the border rows of each site, shows that yield data of cultivars on IDC-sites is a measure of the yield on the IDC portions of each field (Table 3). There is only a trivial

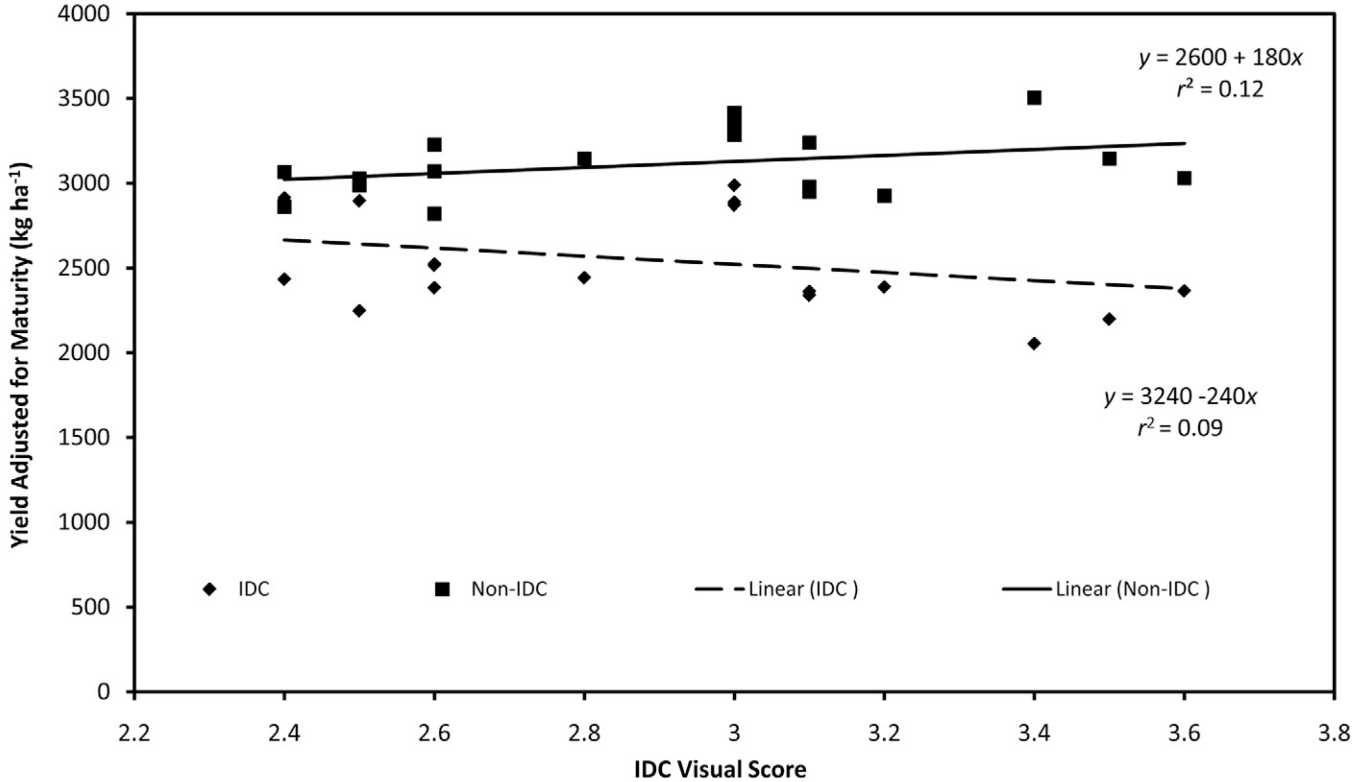

Fig. 1. Regression of yield adjusted for maturity on visual rating for iron-deficiency chlorosis (IDC) score (based on hill plots for IDC). The solid line represents yield, averaged across five environments, for non-IDC portions of a field; and the dashed line represents yield for the IDC portions of each field, averaged across the same five North and South Dakota environments.

amount of IDC observed on the IDC-susceptible cultivar at non-IDC sites.

There were significant differences among cultivars and also among sites within environments for yield (Table 2). When only the IDC-sites were analyzed for yield and all five environments were included in a separate analysis of variance, the cultivar source of variation was significant ($P = 0.01$, ANOVA table not shown). When only the non-IDC sites were analyzed for yield and all five environments were included, the cultivar source of variation was significant ($P = 0.01$, ANOVA table not shown). This result justifies comparing the yield of cultivars within the IDC-sites, and also justifies comparing the yield of cultivars within the non-IDC sites, averaged across environments. There were significant differences among cultivars for visual IDC ratings, based on hill-plot ratings that had been averaged across four locations and two different stages of crop development ($P = 0.01$, ANOVA table not shown).

Soil pH and CCE were generally higher in IDC than non-IDC sites. The exception to this was at Brookings, SD, in 2006. (Table 1). Although visual IDC scores were not taken at the 2007 Brookings sites, relative leaf chlorophyll concentration were obtained using a SPAD meter. The SPAD readings for the V2–V4 and also for the R2–R3 growth stages were significantly different ($P < 0.05$) between sites at the 2007 Brookings, SD, environment. At the V2 to V4 growth stage, the SPAD reading was 30 for the IDC site and 35 for the non-IDC site. At the R2 to R3 growth stage, the SPAD reading was 34 for the IDC site and 38 for the non-IDC site. These SPAD readings show that the IDC site had greater IDC than the non-IDC site for Brookings, SD, in 2007.

Iron-Deficiency Chlorosis Visual Rating is Not a Good Indication of Cultivar Yield on an Iron-Deficiency Chlorosis Site

Within each environment, cultivars responded differently to the IDC and non-IDC soil conditions, relative to each other, which is evidence of a soil type × cultivar interaction (Table 2). Cultivars that yielded the most on IDC sites would not be the best choice on the non-IDC sites (Table 4). For example, Dakota-3 matured 20 September and Dakota-16 matured at a similar date. Dakota-3 had an IDC visual score rating of 2.5, while Dakota-16 had an IDC visual score rating of 3.4. Dakota-3 yielded more than Dakota-16 on the IDC sites, while Dakota-16 yielded more than Dakota-3 on the non-IDC sites. This shows that a cultivar that has high yield on the IDC areas of the field may not be the best cultivar for the non-IDC areas of that field.

Dakota-11, with an IDC visual score rating of 3.0, was the top-yielding cultivar on the IDC sites and was ranked second for yield on the non-IDC sites (Table 4). Dakota-11 matured 23 September, which is similar to Dakota-3 and Dakota-16. This is evidence that some cultivars have high yield on both the IDC and non-IDC areas of a field. Although Dakota-11 had a significantly worse visual score IDC rating than Dakota-3, the yield of these two cultivars were the same on the IDC sites. These results suggest that cultivar selection for sites prone to IDC, should be based on prior yield evaluations at IDC-sites, not based on visual ratings scores for IDC.

Dakota-11 yielded the same as Dakota-3 on the IDC sites, but Dakota-11 yielded more than Dakota-3 on the non-IDC sites (Table 4). The greater IDC tolerance of Dakota-3 resulted

Table 3. Iron-deficiency chlorosis (IDC) visual ratings of the IDC-susceptible check cultivar that was planted on the extreme edges of each site and was common to all locations, across maturity groups. Visual ratings for IDC were taken at the V2–V4 and also at the R2–R3 growth stages. Visual ratings were not taken at the 2007 Brookings, SD site.

		Visual rating score†			
		V2–V4 stage		R2–R3 stage	
Year	Location	IDC site	Non-IDC site	IDC site	Non-IDC site
2006	Arthur, ND	4.8	1.0	3.3	1.0
2006	Brookings, SD	3.0	1.0	2.7	1.0
2007	Hunter, ND	4.4	2.0	4.8	1.0
2007	Galchutt, ND	3.5	1.1	3.6	1.0
2007	Brookings, SD	–	–	–	–
LSD (0.05)‡		0.6		0.6	
2006	Tribune, KS	4.2	1.7	4.3	1.7
2006	Zeandale, KS	4.0	2.7	1.2	1.0
2007	Tribune, KS	2.5	1.0	2.3	1.0
2007	Zeandale, KS	1.5	2.0	2.0	2.0
LSD (0.05)‡		0.5		0.3	

† Rating scale of 1 = no chlorosis, 5 = severe stunting and chlorosis damage to the growing point. Visual ratings in this table are the mean of the check cultivar, averaged across 12 data points, each data point was for a different range within the same row.

‡ Least significant difference for comparing the same check cultivar within the same growth stage, year and location combination, across different sites within the same field.

in a decreased yield of 6% when the yield of this cultivar was compared on IDC sites versus non-IDC sites. Yield of Dakota-11 decreased 13% when the yield of that cultivar was compared on IDC sites versus non-IDC sites. The equal yield of Dakota-11 and Dakota-3 on IDC sites is explained by the higher yield of Dakota-11 on non-IDC sites, which compensated for the decreased tolerance of Dakota-11 to IDC.

Further evidence that visual rating scores for IDC are not an adequate measure of the yield on IDC sites can be found by comparing the yield, averaged across the IDC sites, for Dakota-4 versus Dakota-3 (Table 4). Both Dakota-4 and Dakota-3 have a visual IDC rating of 2.5. However, Dakota-4 had lower yields than Dakota-3 on IDC sites. Although Dakota-4 matures earlier than Dakota-3, yield of these two cultivars was similar on IDC-sites. The comparisons of Dakota 3 versus Dakota 11 and also comparison of Dakota-3 versus Dakota-4 show that IDC visual ratings are not a reliable measure of yield on IDC sites.

Yield is Influenced by Both Genotype and Presence or Absence of Iron-Deficiency Chlorosis

The cultivar × site within environment interaction was further analyzed by regression of yield (adjusted for maturity) on IDC score (hill-plot data), using a separate regression for the IDC and non-IDC sites (Fig. 1). The difference between the slopes of the two regression lines was significant ($P = 0.01$). The form of the two regression lines (Fig. 1) for the North Dakota and South Dakota data are:

$$\text{IDC ADJYLD} = 3240 - 240\,x_i;$$

$$\text{Non-IDC ADJYLD} = 2600 + 180\,x_i;$$

where IDC ADJYLD is the yield averaged across the iron-deficiency chlorosis sites after adjustment for maturity measured on IDC sites; non-IDC ADJYLD is the yield, averaged across non-iron-deficiency chlorosis sites after adjustment for maturity measured on non-IDC sites, and x_i is the IDC score of a particular cultivar averaged across replicates, growth stages, and locations of hill plots.

Table 4. Yield of 18 soybean cultivars on iron-deficiency chlorosis (IDC) and non-IDC paired sites, IDC visual rating scores, and maturity, averaged across five environments in North Dakota and South Dakota. Yield was not adjusted for maturity in this table.

Cultivar	Yield: IDC site	Yield: Non-IDC site	IDC rating score†	Maturity date
	kg ha^{-1}			
Dakota-1	2970	3010	2.4	24 Sept.
Dakota-2	2290	2930	2.4	13 Sept.
Dakota-3	2860	3030	2.5	20 Sept.
Dakota-4	2160	2900	2.5	15 Sept.
Dakota-5	2260	2920	2.6	14 Sept.
Dakota-6	2520	2880	2.6	21 Sept.
Dakota-7	2420	3060	2.6	14 Sept.
Dakota-8	2460	3060	2.8	19 Sept.
Dakota-9	2890	3350	3.0	21 Sept.
Dakota-10	2890	3310	3.0	20 Sept.
Dakota-11	3030	3500	3.0	23 Sept.
Dakota-12	2410	3090	3.1	24 Sept.
Dakota-13	2410	2870	3.1	19 Sept.
Dakota-14	2990	3260	3.1	21 Sept.
Dakota-15	2360	2850	3.2	18 Sept.
Dakota-16	2100	3560	3.4	22 Sept.
Dakota-17	2330	3340	3.5	27 Sept.
Dakota-18	2460	3110	3.6	24 Sept.
LSD (0.05)‡	430	300	0.2	3
LSD (0.05)§	250			

† Rating scale of 1 = no chlorosis, 5 = severe stunting and chlorosis damage to the growing point, averaged across ratings taken at two growth stages. Ratings were taken on hill-plots and not on the yield-trial plots.

‡ Least significant difference for comparing the mean yield of two cultivars within the same column.

§ Least significant difference for comparing the mean yields of a cultivar in the same row.

The results of Fig. 1 show that, on the IDC areas of the field, cultivars with a good IDC visual rating will on average yield more than cultivars with a poor IDC visual rating. On the non-IDC portions of the field, cultivars with poor IDC visual ratings will, on average, yield more than cultivars with a good IDC rating. This is evidence of a *yield drag*. Selection for IDC tolerance tended to select cultivars that were lower-yielding types, in the absence of IDC. The cultivar that was the highest yielding on the IDC areas of the field was not the best-yielding cultivar on the non-IDC areas of that field.

Our results are similar to Froehlich and Fehr (1981). They evaluated 15 soybean genotypes on calcareous and noncalcareous areas of the same field. The genotypes that were the highest yielding on the noncalcareous areas of a field were among the lowest-yielding cultivars on the calcareous areas of that field. The genotypes that were the highest yielding on the calcareous areas of the field tended to have only average yield on the noncalcareous areas of that field.

However, our results differ from those of Niebur and Fehr (1981). Niebur and Fehr selected the 19 most IDC-tolerant genotypes out of 110 genotypes that had previously showed a good level of IDC-tolerance. The visual IDC rating of these 19 genotypes varied from 1 to 1.5, using the same rating scale that we used. They evaluated these 19 genotypes on calcareous and noncalcareous soils and reported that IDC-tolerant genotypes can be selected for yield on noncalcareous soil. In this manuscript, we found the opposite result of Niebur and Fehr (1981). Our results show that the use of visual IDC scores, combined with yield on noncalcareous sites, is not sufficient for identifying cultivars that are high-yielding on IDC sites. We evaluated cultivars with a wider range of IDC visual rating scores than did Niebur and Fehr (1981).

Planting Two Cultivars versus Planting a Single Cultivar

It would be difficult to find IDC yield-testing sites that would be large enough and uniform enough to provide reliable yield data for IDC soil conditions. Perhaps 100 different commercial cultivars would need to be tested for yield each year, at three IDC locations to provide yield data of different genotypes under IDC conditions. For this reason, it may be more realistic to provide visual IDC ratings for a large number of cultivars using hill-plots or short-rows. Hill-plot or short-row experimental units take up less land area than yield-trial plots.

Yield data would then be measured only on non-IDC sites, replicated within each site, and averaged across at least three sites per year. These data would be conducive to identifying a high-yielding cultivar for the non-IDC portions of a field and then using the IDC visual rating data to identify a cultivar for the IDC-prone portions of that field. In this scheme, two different cultivars would be planted on the same field, based on previous global positioning satellite (GPS) mapping of the IDC-prone portions of the field.

If growers only had visual ratings for IDC, then planting a cultivar with good visual IDC rating on the IDC-susceptible areas of the field would be a good approach to increasing yield on the IDC-prone areas of a field. Growers would then use the yield from non-IDC sites to select a cultivar for the non-IDC areas of a field (Table 5). Yield of a field with IDC present on 0 to 100% of the area of that field was simulated using the cultivar mean yield and IDC scores provided in Table 4. For example, if the field had 50% of the area with IDC and Dakota-3 was planted to the IDC area of that field, while Dakota-16 was planted to the non-IDC areas of that field, the overall yield of that field was estimated to be 3210 kg ha^{-1}. Dakota-16 yielded 3560 kg ha^{-1} on the non-IDC sites and Dakota-3 yielded 2860 kg ha^{-1} on the IDC sites (Table 4). The simulated yield of a field planted to Dakota-16 on the 50% non-IDC area and planted to Dakota-3 on the IDC area of that field would be equal to $(0.5 \times 3560) + (0.5 \times 2860) = 3210$ kg ha^{-1} (Table 5). The scheme of planting two different cultivars in the same field, when 50% of the area of the field has IDC, resulted in higher yield for the whole field compared with planting the entire field to a single cultivar of either Dakota-16 or Dakota-3.

With precision farming technology, a planter could be developed that would change cultivars as the planter proceeded across a field. If growers only had yield information on non-IDC areas and IDC visual ratings from IDC areas, for a set of cultivars, there would be merit in planting two cultivars in the same field. In this scheme, the IDC portion of the field would be planted with a cultivar that had a good visual IDC score and the non-IDC portion of that field would be planted with a cultivar with the highest yield potenial (Table 5).

Table 5. The predicted yield of a field that has portions of the field that have iron-deficiency chlorosis (IDC), as well as portions of the field that do not have IDC for North Dakota and South Dakota data. The areas of the field that do not have IDC are planted to Dakota-16 (sensitive to IDC). The areas of the field that have IDC are planted to Dakota-3 (tolerant to IDC). The scheme of planting two different cultivars on the same field is compared with planting only Dakota-11 for the whole field. Yield is not adjusted for maturity in this table.

Percentage of field with IDC	Yield with Dakota-16 only	Yield with Dakota-3 only	Yield with Dakota-16 and Dakota-3	Yield with Dakota-11 only
	kg ha^{-1}			
0	3560	3030	3560	3500
25	3200	2990	3390	3380
50	2830	2950	3210	3270
75	2470	2900	3040	3150
100	2100	2860	2860	3030
LSD (0.05)†		250		

† Least significant difference for comparing two means in the same row (or column) or two predicted means in the same row (or column).

Hansen et al. (2003) stated that neither soil pH nor CCE can be used to accurately identify IDC areas. For this reason, soybean growers need to visually identify these areas in years they are growing soybean. Hansen et al. (2003) also reported that the problem of IDC "exists even though the majority of producers are selecting chlorosis-resistant varieties." These findings suggest that planting an IDC-resistant cultivar on the IDC-susceptible areas of a field will not eliminate IDC, but will increase yields.

If the soybean yields were known in IDC and non-IDC areas, then this information could be used to identify a single cultivar for an entire field. However, this information is not typically available. For example, planting Dakota-11 would maximize yields in many fields (Table 4). These results were unexpected because this cultivar had an IDC score of 3.0 in IDC areas (Table 4).

Kansas

The cultivar source of variation for yield was not significant for the Kansas data (Table 2). However, the cultivar × site within environment source of variation was significant for yield (Table 2). The cultivar × site within environment source of variation was significant ($P = 0.01$) for IDC ratings at the V2–V4 stage and also the R2–R3 stage (ANOVA table not shown). The cultivar source of variation for IDC ratings at the V2–V4 stage and also at the R2–R3 stage were not significant (ANOVA table not shown). For the Kansas data, there were significant differences among cultivars for IDC visual ratings, as measured on yield-trial plots at the IDC sites ($P = 0.01$, ANOVA table not shown).

The cultivar × site within environment interaction was further analyzed by regression of yield (adjusted for maturity) on IDC score, using a separate regression for the IDC and non-IDC sites. The form of the two regression lines for the Kansas data are

$$\text{IDC ADJYLD} = 2890 - 400\,x_i;$$

$$\text{Non-IDC ADJYLD} = 3400 - 230\,x_i;$$

Table 6. Yield of 20 soybean cultivars on iron-deficiency chlorosis (IDC) and non-IDC paired sites, IDC visual rating scores, and maturity, averaged across four environments in Kansas. Yield is not adjusted for maturity in this Table.

Cultivar	Yield		IDC rating score†	Maturity date
	IDC site	Non-IDC site		
	kg ha^{-1}			
Kansas-1	2310	3150	1.0	27 Sept.
Kansas-2	2470	2940	1.7	25 Sept.
Kansas-3	2520	2970	1.7	4 Oct.
Kansas-4	1880	2860	1.8	26 Sept.
Kansas-5	1980	3020	1.8	30 Sept.
Kansas-6	1850	3110	1.9	26 Sept.
Kansas-7	1760	2800	2.2	2 Oct.
Kansas-8	1920	2680	2.2	30 Sept.
Kansas-9	2030	2900	2.3	27 Sept.
Kansas-10	2100	2870	2.3	1 Oct.
Kansas-11	1990	2650	2.5	2 Oct.
Kansas-12	1990	3110	2.5	1 Oct.
Kansas-13	1600	2840	2.6	27 Sept.
Kansas-14	1750	2920	2.6	2 Oct.
Kansas-15	1880	2750	2.7	29 Sept.
Kansas-16	1860	2990	2.7	2 Oct.
Kansas-17	2350	2790	2.7	1 Oct.
Kansas-18	1770	2660	2.8	28 Sept.
Kansas-19	1790	2550	2.9	4 Oct.
Kansas-20	1470	2760	3.3	4 Oct.
LSD (0.05)‡	700	440	0.9	2
LSD (0.05)§	620			

† Rating scale at the V2–V4 stage; 1 = no chlorosis, 5 = severe stunting and chlorosis damage to the growing point. Ratings were taken on yield-trial plots.

‡ Least significant difference for comparing the mean yield of two cultivars within the same column.

§ Least significant difference for comparing the mean yield of a cultivar in the same row.

where IDC ADJYLD is the yield averaged across the IDC sites after adjustment for maturity measured on IDC sites; non-IDC ADJYLD is the yield, averaged across non-IDC sites after adjustment for maturity that was measured on non-IDC sites, and x_i is the IDC score of a particular cultivar averaged across replicates and locations. The difference between the slopes of these regression lines was not significant. Both slopes were negative. This result suggests that cultivars with the best IDC visual score were the highest-yielding cultivars for both IDC and non-IDC areas (Table 6). Visual IDC-score data, combined with yield data on non-IDC sites, should be sufficient to identify the best cultivars for IDC-prone fields in Kansas. It would not be necessary to plant two different cultivars in the same field in Kansas because the same cultivar is highest-yielding on both the IDC and non-IDC portions of that field.

CONCLUSIONS

The results from North Dakota and South Dakota showed that the highest-yielding cultivar on the non-IDC areas of the field had a poor IDC visual score. Typically, only IDC visual-score and yield on non-IDC sites is available when selecting cultivars for fields that have IDC. In this situation, yield will be increased in North Dakota and South Dakota by planting two different cultivars on the same field. If replicated yield data of a large number of cultivars was available in North and South Dakota, for both IDC sites and non-IDC sites, then a single high-yielding cultivar could be identified for the whole field. The results from Kansas showed that the highest-yielding cultivars on the non-IDC areas of the field also had a good IDC visual score. This result showed that in Kansas, yield can be maximized by planting a single high-yielding cultivar across both the IDC and non-IDC portions of fields. The results of the experiments conducted using Maturity Group 0 cultivars were not the same as the results of the experiments conducted using Maturity Group 3 and 4 cultivars. We do not know whether this is due to the particular cultivars that happened to be chosen in these different maturity zones, or whether there are fundamentally different genetic relationships between IDC visual score and yield in different parts of the United States.

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REFERENCES

Casler, M.D. 1982. Genotype × environment interaction bias to parent-offspring regression heritability estimates. Crop Sci. 22:540–542.

Fehr, W.R., and C.E. Caviness. 1977. Stages of soybean development. Iowa State Univ. Spec. Rep. 80. Iowa State Univ., Ames.

Franzen, D.W., and J.L. Richardson. 2000. Soil factors affecting iron chlorosis of soybean in the Red River Valley of North Dakota and Minnesota. J. Plant Nutr. 23(1):67–78.

Froehlich, D.M., and W.R. Fehr. 1981. Agronomic performance of soybeans with differing levels of iron-deficiency chlorosis on calcareous soil. Crop Sci. 21:438–441.

Goos, R.J., and B.E. Johnson. 2000. A comparison of three methods for reducing iron- deficiency chlorosis in soybean. Agron. J. 92:1135–1139.

Hansen, N.C., M.A. Schmitt, J.E. Anderson, and J.S. Strock. 2003. Iron deficiency of soybean in the upper Midwest and associated soil properties. Agron. J. 95:1595–1601.

Miller, J.E., and W.R. Fehr. 1979. Direct and indirect recurrent selection for protein in soybeans. Crop Sci. 19:101–106.

Naeve, S.L., and G.W. Rehm. 2006. Genotype × environment interactions within iron- deficiency chlorosis-tolerant soybean genotypes. Agron. J. 98:808–814.

Niebur, W.S., and W.R. Fehr. 1981. Agronomic evaluation of soybean genotypes resistant to iron-deficiency chlorosis. Crop Sci. 21:551–554.

SAS Institute. 2004. SAS user's guide. v. 9. SAS Inst., Cary, NC.

Steel, R.G.D., and J.H. Torrie. 1960. Principles and procedures of statistics. McGraw- Hill Book Company, New York.