Soil pH and carbonate effects on soybean yields

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Soil pH and carbonate effects on soybean yields

by

Natalia Rogovska

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Soil Science (Soil Fertility)

Program of Study Committee:
Alfred M. Blackmer, Major Professor
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Iowa State University
Ames, Iowa
2004
Graduate College
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This is to certify that the master's thesis of

Natalia Rogovska

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy
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ABSTRACT

Soybean plants [Glycine max (L.) Merrill] often show symptoms of iron deficiency chlorosis on calcareous soils. Good relationships between soil properties and yields have been difficult to establish, however, presumably because these relationships are altered by many different factors at specific sites. We studied relationships between soybean grain yields and soil pH and carbonate content within 12 Iowa fields expected to have marked variability in these soil properties and showing marked variability in soybean growth. Remote sensing of soybean canopy was used to help identify appropriate fields and sampling areas within fields. Plant and soil samples were collected in each area and grain yields were related to measured soil pH and carbonate content. Soybean yields decreased with increases in pH and increases in carbonate content. An index of soil-based stress that considers both measured soil pH and carbonate content was developed, and this index explained >50% of the within-field variability in yields. This relationship can be used to characterize the suitability of fields for soybean growth. The results also demonstrate how remote sensing can be used to map spatial patterns in the degree of plant stress symptoms in fields and use this information to define efficient sampling strategies to identify the soil factors associated with this stress.
INTRODUCTION

Literature review

Soybeans are extensively grown in areas of the Corn Belt where fields often have areas of relatively acid (pH < 6) and areas of highly calcareous soils intermingled in complex spatial patterns. Calcareous soils are defined as soils containing sufficient CaCO$_3$ and MgCO$_3$ to effervesce visibly when treated with a strong acid (SSSA, 1997). Amounts of carbonate are expressed in terms of calcium carbonate equivalent (CCE). Soil pH is highly buffered by carbonates and bicarbonates in calcareous soils, and measured pH values usually range from 7.5 to 8.3 depending on concentration of CO$_2$ and other factors (Loeppert, 1986; Bloom, 2000).

The complex spatial patterns in Des Moines lobe were formed as the soils developed by weathering of calcareous parent materials deposited during the past 12,000 years (Rabenhorst et al., 1991; Prior, 1997). Major processes involved are leaching of all carbonates from the surface soils on much of the landscape and net upward movement of water and accumulation of carbonates around the edges of water-filled depressions that were common on much of the natural landscape. The depressions were drained to produce agricultural soils during the past 150 years, and the carbonate content of these soils often varies greatly
within a distance of a few meters (Mendenhall, 1967). Calcareous areas in fields are also produced by erosion of surface soil from knolls and side slopes.

Soybean plants tend to have yellow leaves and grow poorly on the calcareous soils, and the symptoms are commonly described as iron deficiency chlorosis. Iron is abundant in essentially all soils, so deficiencies of iron are caused by interactions of several factors that control the solubility of iron in the soil solution and (or) plant sap (Brown et al., 1959a, b; Walter and Aldrich, 1970; Coulombe et al., 1984; Fleming et al., 1984; Loeppert, 1986; Marschner et al., 1986; Camp et al., 1987; Mengel, 1994; Nikolic and Romheld, 1999; Romheld 2000). The solubility of iron is known to decrease with increases in pH and bicarbonate content, which are interrelated through pH-buffering by equilibria between $\text{H}_2\text{CO}_3$, $\text{HCO}_3^-$, and $\text{CO}_3^{2-}$ (Loeppert, 1986; Bloom, 2000).

Soil water content can influence concentrations of iron in solution by controlling soil aeration because concentrations of $\text{CO}_2$ in the soil atmosphere influence soil pH and bicarbonate concentrations. In addition, concentrations of $\text{O}_2$ influence soil redox potential and the ratio of relatively soluble $\text{Fe}^{2+}$ to relatively insoluble $\text{Fe}^{3+}$ (Chen and Barak, 1982; Inskeep and Bloom, 1984). It is not surprising, therefore, that the intensity of symptoms of iron deficiency chlorosis within any given area tend to vary with year to year variation in soil moisture regimes (Inskeep and Bloom, 1986; Bloom and Inskeep, 1986). Due to
the effects of soil moisture, the size and shape of chlorotic areas in fields tend to vary from year-to-year, so it is difficult to establish good relationships between stable soil properties and intensity of symptoms of iron deficiency chlorosis in plants. It also is difficult to define the exact size and shape of soil areas where specified levels of iron deficiency chlorosis symptoms should be expected. Existing evidence, therefore, suggests that iron deficiency chlorosis is caused by an interaction of soil properties (soil pH and carbonate content) that are stable in the sense that they do not vary within a period of a few years and soil conditions (moisture content, CO$_2$ concentrations, HCO$_3^-$ concentrations, O$_2$ levels, ratios of soluble Fe$^{+2}$ to insoluble Fe$^{+3}$) that are transient in the sense that they vary greatly with time on the scale of days to years.

The task of enumerating the causes of iron deficiency chlorosis is complicated by the effects of other factors such as high concentrations of NaCl and infestation of soybean cyst nematodes (Heterodera glycines Ichinohe). Both of these factors produce plant symptoms similar to iron deficiency chlorosis (Levitt, 1980; Niblack and Norton, 1992; Niblack, 1999; Tylka, 1995; Tylka, 2001).

Another problem in enumerating the causes of iron deficiency chlorosis is that soybean varieties differ in sensitivity. Plant breeding programs have been successful in developing varieties having high resistance to iron deficiency chlorosis as indicated by leaf-color ratings of young plants growing on calcareous soils (Cianzio et al., 1979; Froehlich and Fehr, 1981; Al-showk et al.,
1986; Charlson et al., 2003). Even for a single variety, however, it has been difficult to establish good relationships between measured soil characteristics and intensity of symptoms in plants.

Observations of spatial patterns in plant size (and canopy cover) within fields, as revealed by aerial photographs, suggested that plant size may be correlated with carbonate concentrations and, therefore, that patterns in plant size may give some indications of spatial patterns in soil carbonate content (Blackmer and Rogovska, 2001). Especially in fields where soybeans were planted in rows 76 cm apart, spatial patterns in plant growth could be easily characterized by analysis of color of an aerial image, which is primarily determined by the amounts of soil showing between rows. As shown by example in Fig. 1, the amount of soybean growth often ranged from complete canopy cover to no canopy cover due to death of soybean seedlings.

Although spatial patterns in plant growth often resemble boundaries on soil map units, the spatial patterns in soybean growth occur in much finer scales than soils are mapped, and the patterns in soybean growth often showed continuous gradation rather than the distinct boundaries imposed by the normal categorical classification of soils into map units. These observations suggest that relationships between the intensity of iron deficiency chlorosis symptoms and soil carbonates may need to consider linear relationships rather than only presence or absence of carbonates. Although it has been recognized that iron
deficiency chlorosis is associated with carbonate presence, linear relations between carbonate content and symptoms of iron deficiency chlorosis have been observed by some researchers (Morris et al., 1990; Franzen and Richardson, 2000) but not others (Anderson, 1982; Clark, 1982; Vose, 1982).

The objective of this study was to assess the percentage of the variation in yields of soybean that could be explained by measured soil pH and carbonate content within fields showing marked spatial variability in plant size and expected to have marked variability in soil pH and carbonate contents. We included soil pH in our studies because soil pH is closely related to carbonate content and iron deficiency chlorosis. Our study was designed to test the hypothesis that remote sensing could be used to select fields and sampling points for effective studies of the relationships between carbonate contents and symptoms of iron deficiency chlorosis within fields, where variability due to variety, weather, and management practices is minimized.

**Thesis organization**

This paper is to be submitted to the Journal of Soil Science Society of Agronomy. Thesis includes abstract, introduction, materials and methods, results and discussions, and conclusion.
Figure 1. Aerial photograph showing spatial patterns in soybean growth within a 36-ha field.
MATERIALS AND METHODS

Studies were conducted in fields within the Clarion-Nicollet-Webster and Canisteo-Nicollet-Webster soil associations of central Iowa. These soils were developed on calcareous glacial till that was deposited about 12,000 years ago (Prior, 1991). The landscape of this area is flat to gently rolling, divided into fields (usually 400 by 800 m) for management, and dominated by a corn-soybean cropping system. Major soil series in the fields studied were Clarion (fine-loamy, mixed, mesic Typic Hapludolls), Nicollet (fine-loamy, mixed, mesic Aquic Hapludolls), Webster (fine-loamy, mixed, mesic Typic Haplaquolls), Harps (fine-loamy, mesic Typic Calciaquolls), Okoboji (fine, montmorillonitic, mesic Cumulic Haplaquolls), and Canisteo (fine-loamy, mixed (calcareous), mesic Typic Endoaquolls).

The first step of our study was to identify fields that showed great variability in yields as revealed by remote sensing. This was accomplished by surveying fields on the flight paths to cornfields that were being photographed for other studies in Greene, Boone, and Story counties. Photographs of selected fields were taken using a 35-mm camera that was hand held and pointed downward through a hole in the bottom of an airplane. The images were taken throughout the growing season to monitor changes in spatial patterns of plant growth. The pictures were taken at a height of 1000 to 1200 m above the ground and the film used was Kodak Elite Chrome 200®. Crop producers who managed
the selected fields were contacted and permission was obtained to conduct studies in these fields.

Data collection areas (0.93 m²) within fields were selected shortly before harvest to include the widest possible range in plant heights and a good distribution of heights within this range. The aerial photographs were used to help select these areas. The data collection areas were selected without specific knowledge of soil pH or carbonate values, although limited information could be obtained from soil survey maps and by applying acid to the soil surface to check for carbonate presence. Special effort was made to locate some data collection areas where plant height was not consistent with expectations from soil survey maps or the qualitative test for carbonate content. All data collection areas were selected to be representative of a surrounding area that was at least 10 m² and reasonably uniform with respect to plant height and density as well as soil color, slope, and other obvious characteristics.

Plant and soil samples were collected from each area. Plant height (ranged from 4 cm to 107 cm) was measured and recorded for each area shortly before harvest. For fields with 76-cm row spacing (all except sites 4 and 12), all plants were collected along 0.61-m segments from each of two rows. For 38-cm row spacing, all plants were collected along 0.61-cm segments from each of four rows. The plants were cut 2 cm above the ground, placed in a paper bag, and then dried at 60°C for 48 hours. Once dried, each plant sample was shelled by hand
and the grain was weighed. The weight of each sample within a field was recorded as relative yield (i.e., percentage of the highest yield obtained within a field). Use of relative rather than absolute yields enabled us to pool data from many different sites.

Soil samples were collected after the harvest. A power auger 15 cm in diameter was used to collect samples to the depth of 15 cm. These samples were taken in the exact location where plant samples were previously collected. Each sample was a composite of 3 cores; the first was taken between the rows harvested for yield calculation, the second and third samples were collected on the right and left sides of the rows. The soil was mixed thoroughly, placed in a cloth bag, and dried at 60°C for 48 hours.

The dry soil samples were crushed to pass a 2-mm sieve and analyzed for pH in water using 1:1 soil:water ratio by using a glass electrode (Fisher Accumet, Model 610 pH meter. Pittsburg, PA) as described by Bloom (2000). Percentage calcium carbonate equivalent (CCE%) was measured using a pressure calcimeter method as described by Boellstorff (1978) except that a digital manometer (MKS Baratron model SP27-78, Burlington, MA) was used to measure amounts of CO₂ produced in 7 min following the addition of acid to the soil. The results are expressed in terms of calcium carbonate equivalent (CCE%) in accordance with accepted conventions.
Relationships between soil-test values (pH and CCE%) and relative yields of grain were evaluated with SigmaPlot 8.0 for Windows (SPSS Inc., Chicago, IL). Outlier analysis was performed on each data set using standardized-studentized residual values and the Bonferroni simultaneous inference approach in SAS system for Windows V8 (SAS Institute Inc., Cary, NC). Outliers were detected by comparing the studentized residuals to a critical value from a t-distribution chosen using a Bonferroni-type adjustment with probability of a type I error 5%. Residuals with absolute value greater than Bonferroni critical value were considered as outliers and were not used in regression analysis. Two outliers were deleted; one in site 1 and one in site 2.
RESULTS AND DISCUSSION

Soil pH Effects

Relationships between soil pH and relative yields within individual sites were statistically significant ($P<0.05$) at 9 of the 12 sites. The $r^2$ values for linear regression ranged from 0.19 to 0.59 and had a mean of 0.37 (Fig. 2). Linear regression analysis of data pooled from all sites showed that soil pH explained 30% of variability in relative yields (Fig. 3). These relationships clearly show that soybean yield levels tended to decrease with increases in soil pH.

A noteworthy problem in Fig. 2 and 3 is that great variability occurred at soil pH values greater than 7.5 and this variability was not related to soil pH. As previously noted, this problem can be explained by the fact that soils having pH $>7.5$ usually have free calcium carbonate, and the pH measured is controlled by chemical equalibria involving partial pressure of $\text{CO}_2$ and other factors. The data above pH 7.5 tend to weaken the validity of the regression analysis. However, means for 0.5-pH-unit intervals (Fig. 3) clearly indicate that yield levels tended to decreases with increase in pH in the range from 5.5 to 7.4. The variability observed in the overall relationship is consistent with the generally accepted idea that one or more factors other than pH influence soybean growth.

Carbonate Effects

Relationships between soil CCE and relative yields within individual sites were statistically significant ($P<0.05$) at 11 of the 12 sites. The $r^2$ values for linear
Figure 2. Relationships between soil pH and relative yields of soybean within 12 fields.
Figure 3. A soil pH - relative yields relationship obtained by pooling data from 12 different fields.
regression ranged from 0.01 to 0.82 and had a mean of 0.58 (Fig. 4). Linear regression analysis of data pooled from all sites showed that soil CCE explained 41% of variability in relative yields (Fig. 5). These relationships clearly show that soybean yield levels tended to decrease with increases in soil carbonate content.

A noteworthy problem in Fig. 4 and 5 is that great variability in relative yields occurred at soil CCE values <5 and this variability was not related to soil CCE. This problem can be explained because soils having CCE values <5 can have great variability in soil pH values. The data below CCE 5 tend to weaken the validity of the regression analysis. However, means for 6-CCE-unit intervals (Fig. 5) clearly indicate that yield levels tended to decrease with increases in CCE values >5. The variability observed in the overall relationship is consistent with the generally accepted idea that one or more factors other than carbonate content influence soybean growth.

Development of a Stress Index

Regression analyses showed that class means for relative yields tended to decrease by 22% for each unit increase in soil pH (Fig. 3). Regression analyses showed that class means for relative yields tended to decrease by 3% for each unit increase in soil CCE (Fig. 5). The slopes of these regressions indicate that the average effect of a CCE unit was 0.14 times the effect of the pH unit on soybean growth. This finding indicates that an index calculated by adding pH and 0.14*CCE could be used to develop a stress index where units of CCE are
Figure 4. Relationships between soil carbonate content and relative yields of soybean within 12 fields.
Figure 5. A soil carbonate content – relative yields relationship obtained by pooling data from 12 different fields.
adjusted to have an average effect on plants equal to the average effect of one pH unit as observed in this study. This index is defined by

\[ SI = \text{pH} + 0.14\text{CCE\%} \]  

Relationships between stress index and relative yields within individual sites were statistically significant \((P<0.05)\) at 11 of the 12 sites, and \(r^2\) values for linear regression ranged from 0.01 to 0.89 and had a mean of 0.57 (Fig. 6). Linear regression analysis of data pooled from all sites showed that stress index explained 45% of variability in relative yields (Fig. 7). This relationship clearly shows that soybean yield levels tended to decrease with increases in stress index. The variability observed in the overall relationship is consistent with the generally accepted idea that one or more factors other than the stress index influence soybean growth.

**Value of the Stress Index**

Figure 8 illustrates that soil pH and CCE\% are expressed in different ranges of the stress index. If it is recognized that the stress index correlates with yields, data in this figure show that either pH or carbonate content can be shown to correlate with the intensity of stress symptoms, but the effect of each can be detected only when the soils are studied in separate classes based on soil carbonate content. Relationships between soil pH and yields, for example, are good only when all soils have carbonate content below some critical value. Relationships between carbonate content and yields, alternatively, are good only
when soils have carbonate value above that critical value. The importance of separating soils based on some critical values of carbonate content to determine the effects of pH is consistent with the well-known buffering effects of carbonate content on pH. The value of the stress index, therefore, is that it separates soils with and without carbonates into different classes and expresses each in units that produce similar amounts of symptoms in plants.

The critical concentration of carbonate content is difficult to precisely define because carbonates can be occluded in large particles and this carbonate is measurable even though it would have essentially no effect on soil pH or stress on plants. Variation of points around the ascending line in Fig. 8A must be attributed to errors in determinations of CCE or to the presence of carbonates occluded within relatively large particles. Figure 8B shows that CCE less than 3% had little or no effect on plant yields and this lack of effect may be due to particles of calcium carbonate that are too large to influence soil pH or plant growth.

Variations in pH values above the plateau are consistent with a range in pH values usually measured in calcareous soils. The fact that a plateau exists supports the idea that soil pH is not influenced by increases in carbonate concentrations after carbonates are present in high enough concentrations to saturate the soil solution.

At pH values greater than about 8, CCE is the major factor affecting the
Figure 6. Relationships between stress index and relative yields of soybean within 12 fields.
Figure 7. A stress index – relative yields relationship obtained by pooling data from 12 different fields.
Figure 8. A partitioning of the stress index into its two components, soil pH (A) and soil carbonate content (B).
value of the stress index. Deviations of points from the 1:1 regression line in Fig. 8B must be due to errors in measurement of soil pH. Comparison of Fig. 8A and Fig. 8B suggests that, as should be expected due to the problem of occluded carbonates, errors associated with measurement of carbonate content were greater than errors associated with measurement of soil pH.

Comments on the Method Used

Use of remote sensing to identify fields that showed marked variability in plant size enabled us to focus on fields and parts of fields where good relationships between soil characteristics and symptoms of stress could be expected. Good relationships could not be expected in the fields that showed no variability in symptoms of stress, either because plants were resistant to the stress, because fields did not have calcareous areas, or because some environmental factors minimized the usual effects of carbonates or pH. This approach is valid because our objective relates to identifying factors that correlate with symptoms rather than to assess the importance of the symptoms within the study area.

The fact that our relationships were established under conditions where symptoms were present does not diminish the importance of our relationships because these relationships can be used as a reference or a baseline for identifying resistance to the stress or environmental factors that minimize the effects of the stress. Without some ability to quantify the level of stress in soils, it
is impossible to distinguish among lack of a stress, plants resistant to this stress and some environmental factor that minimizes the stress. The underlying problem is that it is difficult to define a stress if the symptoms of the stress cannot be related to a measurable soil characteristic.

The use of remote sensing made it possible to select sampling areas (within fields) that showed a wide range of plant symptoms and a good distribution of plant symptoms within this range. This approach is valid because our objective was to quantitatively assess the ability of soil test values to explain variability in the symptoms and because the soil test values were not known when the sampling areas were selected. The wide range and good distribution of plant stress levels is very important because the interaction of soil pH and carbonate content cannot be established within a narrow range in pH or carbonate values. Indeed, the nature of the interaction between soil pH and carbonate content is such that neither will show a good relationship with plant symptoms in situations where data from soils with and without carbonates are pooled to form a single relationship unless a few samples with very low pH or high carbonates are present.

The use of small sampling areas was critical to our study because soil carbonate concentrations often varied greatly within a distance of a few meters. Problems caused by collecting very small samples were minimized by selecting sampling areas where plant symptoms appeared relatively uniform within a
larger area. The relationships between yields and soil test values observed in this study clearly indicate that much of the variation in yield was due to pH and carbonate content. The high degree of spatial variability in plant size within areas of a few square meters, therefore, indicates that pH and carbonate content often varied on scales small enough to prohibit the use of larger test areas. The underlying problem avoided by using small areas is that, as noted by Cline (1944), a soil sample collected within a highly variable area is not representative of the area. For this reason, relationships between soil test values and yields should not be expected unless the soils are somehow classified by pH or carbonate content before samples are collected.

Analyses of soil samples collected within sampling areas were used to objectively assess the portion of the total variability in yield that can be explained by the soil factors measured. Plant varieties, management practices, and weather were similar at sampling sites within fields, but these factors were not necessarily similar among different fields. This overall approach may have great potential for disaggregating the effects of many different soil factors that can interact in complex ways to cause various levels of stress on plants and produce somewhat similar symptoms.

The percentages of variability explained by soil pH, carbonate content, and the stress index seem surprisingly good if it is recognized that spatial variability can be attributed to many factors other than pH or CCE% (i.e. stress
due to moisture, weeds, insects, diseases, etc.). If we had observed no relationship between relative yields and pH or CCE, we could not conclude that these factors did not have effects on yields because the effects could have been masked or obscured by other factors. The fact that we observed these relationships provides compelling evidence that pH and carbonate content influenced soybean growth.
CONCLUSIONS

Yields of soybean tended to decrease with increases in soil pH and with increase in soil carbonate content within fields. However, the effects of these increases varied from field to field. Moreover, these two factors interacted in the way that the effects of one factor often obscure the effects of the other factor. A new stress index can solve this problem by separating soils with and without carbonates into different classes and expressing each in unit that produce similar amounts of symptoms in plants.

Remote sensing of plant canopies offers a promising way to select fields and sampling points within fields for efficient studies to define relationships between soil properties and crop growth. This approach minimizes sampling problems caused by variations in soil properties that occur in complex spatial patterns within a field. Remote sensing essentially classifies soils before samples are collected, and regression analyses between measured soil properties and measured yields are used to define the relationships.
REFERENCES CITED


SPSS Inc. 2002. SigmaPlot 8.0 for Windows. SPSS Inc., Ghicago, IL.


ACKNOWLEDGMENTS

This research was supported by funding from the Iowa Soybean Promotion Board.

I would like to take this opportunity and express my gratitude to my major professor, Alfred Blackmer, for his invaluable counseling and guidance throughout the course of the study and for extending me the opportunity to pursue my degree at Iowa State University. I very much appreciate his friendly advice, moral support, and help in writing this thesis.

The willingness of Antonio Mallarino to serve in my graduate committee is greatly appreciated. I am thankful to Gregory Tylka for serving in my committee and helping with some relevant laboratory analyses.

My work would not be possible without the help of our “nitrogen group”; Jun Zhang, Peter Kyveryga, Brad Van De Woestyne, Gaylia Ostermeier, Mark Glady, Eric Phipps, Ben Van Beek, Jason Gibson, Dustin Bollig and Nate Hertel. Julie Blackmer deserves special thanks for her willingness to help shelling soybeans.

I wish to express my sincere appreciation to Dianne Blackmer for her thoughtfulness, hospitality, and kindness to me and my family. No words can explicit my thankfulness to my husband Peter for his encouragement and staying by me in good times and bad times. I thank my daughter Victoria for making every day special by greeting me with smiles, hugs, and kisses every morning.

Extra special thanks are extended to my parents, especially my mother, who knew the importance of education and encouraged me to pursue the higher levels of it. Thank you all.