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Soil Electrical Conductivity as a Crop Productivity Measure for Claypan Soils

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Inexpensive and accurate methods for spatially measuring soil properties are needed that enhance interpretation of yield maps and improve planning for site-specific management. This study was conducted to investigate the relationship of apparent profile soil electrical conductivity (EC_a) and grain yield on claypan soils (Udollic Ochraqualfs). Grain yield data were obtained by combine yield monitoring and EC_a by a mobile, on-the-go electromagnetic (EM) induction meter. Investigations were made on four claypan fields between 1993 and 1997 for a total of 13 site-years. Crops included five site-years of corn (*Zea mays* L.), seven site-years of soybean [*Glycine max* (L.) Merr.], and one site-year of grain sorghum [*Sorghum bicolor* (L) Moench]. Transformed EC_a ($1/EC_a$) was regressed to topsoil thickness giving r^2 values > 0.75 for three of the four fields. The relationship between grain yield and EC_a was examined for each site-year in scatter plots. A boundary line using a log-normal function was fit to the upper edge of data in the scatter plots. A significant relationship between grain yield and EC_a (boundary lines with $r^2 > 0.25$ in nine out of 13 site-years) was apparent, but climate, crop type, and specific field information was needed to explain the shape of the potential yield by EC_a interaction. Boundary line data of each site-year fell into one of four condition categories: Condition 1—site-years where yield increased with decreasing EC_a; Condition 2—site-years where yield decreased with decreasing EC_a; Condition 3—where yield was less at low and high EC_a values and highest at some mid-range values of EC_a; and Condition 4—site-years where yield variation was mostly unrelated to EC_a. Soil EC_a provided a measure of the within-field soil differences associated with topsoil thickness, which for these claypan soils is a measure of root-zone suitability for crop growth and yield.

THE FORMATION OF SOIL over landscapes along with management-induced soil changes (e.g., accelerated erosion with tillage, lime, and fertilizer amendments) results in soil variation within cropped fields that affects productivity. A soil characteristic often causing variability in crop production is soil water storage for plant growth. Soil water storage is a composite of many measurable properties including water infiltration rate, soil texture and structure, soil water adsorption and desorption, soil depth, landscape features (i.e., slope, landform, aspect), restrictive soil layers, soil organic matter, and surface residue. Some of these same soil properties physically affect crop root growth. With the advent of site-specific management strategies (often referred to as precision agriculture), interest in being able to cost-effectively measure spatially variable soil characteristics that affect crop growth has intensified.

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Traditional soil surveys often provide estimates of crop productivity for each soil mapping unit. In the USA, county soil surveys report the average grain yield of major crops by soil series. Slope position and landform are topographic features that also have been used to explain crop productivity relationships (Hanna et al., 1982; Spomer and Piest, 1982; Jones et al., 1989; Wood et al., 1991; Mulla et al., 1992; Jaynes et al., 1995; Khakural et al., 1996a; McConkey et al., 1997; McGee et al., 1997; Sudduth et al., 1997; Timlin et al., 1998). Generally, footslope positions out-yield upslope positions unless poor drainage caused ponding. More detailed soil productivity indices have also been developed using soil properties to characterize variability between soil types at field-level (Neill, 1979; Scrivner et al., 1985a, b; Persinger and Vogt, 1995; Khakural et al., 1996b) and regional (Pierce et al., 1983, 1984; Schumacher et al., 1994) scales. However, measurements required to calculate soil productivity indices on individual fields are expensive and time consuming, since site evaluation through deep soil sampling and follow-up lab analysis is required. Thus, the use of productivity indices for individual fields by producers has not been widely adopted.

Spatially referenced soil sampling either by soil mapping unit or on a regular grid is now routinely used to create maps for variable-rate fertilizer and lime applications. Surface soil organic matter content determined from spatially referenced samples has sometimes been used to explain variability in crop production (Mallarino et al., 1996; Buciene and Svedas, 1997; Mulla and Bhatti, 1997). Variation in crop yield has also been correlated to surface soil texture (Khakural et al., 1996a; McBratney and Pringle, 1997).

Direct measurement of spatial crop productivity by yield monitoring and mapping has been offered as another method to map soil variability (Lark and Stafford, 1996). However, yield maps are confounded by many potential causes of yield variability (Pierce et al., 1997) as well as potential error sources (Blackmore and Marshall, 1996). Using yield maps alone to identify the influence of soil and landscape properties on crop production without also using spatial measurement of the numerous other potential and often transient yield-limiting factors (e.g., pest incidence, nutrients, and management variation) may be futile. Averaging multiple years of yield maps has been suggested as one way of establishing stable yield productivity patterns related to soil properties (Kitchen et al., 1995; Stafford et al., 1996; Colvin et al., 1997). However in some regions, high producing areas of a field during "dry" years can be low producing areas of the same field in "wet" years (Wibawa et al., 1993; Colvin et al., 1997; Sudduth et al., 1997). Averaging yield maps may neutralize the information needed to better understand the interaction between soil/landscape properties and climate for crop production (Sawyer, 1994).

Abbreviations: CF, claypan field; EC_a, apparent soil electrical conductivity; EM, electromagnetic induction.

Table 1. Soil association and cropping history information from 1993–1997 for four claypan soil fields.†

	Claypan field 1	Claypan field 2	Claypan field 3	Claypan field 4
Field size (acres)	88	68	33	32
Soil association‡	Putnam-Mexico	Putnam-Mexico	Putnam-Mexico	Mexico-Leonard-Armstrong-Lindley
Cropping history:				
1993	mulch-till, planter, 30 in. rows, corn	--	--	--
1994	mulch-till, planter, 30 in. rows, soybean	--	--	--
1995	mulch-till, planter, 30 in. rows, grain sorghum	mulch-till, drill, 15 in. rows, soybean	--	no-till, drill, 7.5 in. rows, soybean
1996	mulch-till, drill, 7.5 in. rows, soybean	no-till, planter, 30 in. rows, corn	no-till, drill, 7.5 in. rows, soybean	no-till, planter, 30 in. rows, corn
1997	mulch-till, planter, 30 in. rows, corn	no-till, drill, 7.5 in. rows, soybean	no-till, planter, 30 in. rows, corn	no-till, drill, 7.5 in. rows, soybean

† Cropping data is only shown for the years where data was obtained for this analysis.
‡ Armstrong, fine, smectitic, mesic Aquertic Hapludalfs; Leonard, fine, smectitic, mesic Vertic Epiaqualfs; Lindley, fine-loamy, mixed, superactive, mesic Typic Hapludalfs; Mexico, fine, smectitic, mesic Aeric Vertic Epiaqualfs; Putnam, fine, smectitic, mesic Vertic Albaqualfs.

Inexpensive and accurate methods for measuring within-field soil productivity variation would greatly improve site-specific crop management. Spatial measurement of profile EC_a has been reported to have potential for predicting crop production variation caused by soil differences (Jaynes et al., 1995; Sudduth et al., 1995). Rapid spatial measurement of soil EC_a has been accomplished using mobile EM induction sensing (McNeil, 1992; Jaynes et al., 1993; Kitchen et al., 1996). Soil EC_a measurements can be used on some soils as a surrogate measure of more costly soil chemical and physical measurements (Jaynes, 1996).

Approximately 10 million acres in northern and northeastern Missouri and southern Illinois have been classified as the Central Claypan Soils (MLRA 113) in the Major Land Resource Area classification system (Soil Survey Staff, 1981). Claypan soils have a unique and complex hydrology controlled by a slow soil-matrix water flow through a restrictive clay layer generally located 0.5 to 2.0 ft below the soil surface (Jamison et al., 1968). During wet periods these soils can remain saturated for days to weeks. Clay content in the argillic horizon is usually > 50% and is comprised of smectitic (high shrink-swell) clay minerals. Claypan soils can have significant soil cracks when dry, with the volume of soil cracks reported as high as 6% (Baer et al., 1993) or 17% (Larson and Allmaras, 1971). Infiltration rates vary greatly and are related to soil moisture content and soil cracking (Jamison and Thornton, 1961; McGinty, 1989). Variations in EC_a measured by EM sensing have been found to be highly correlated to the topsoil thickness (depth to the argillic horizon) for these claypan soils (Doolittle et al., 1994).

Crop productivity on claypan soils as affected by topsoil thickness has been documented. Corn yield on a claypan soil with no topsoil was half that produced with a topsoil thickness of 15 in. (Thompson et al., 1991). Claypan soil topsoil thickness accounted for 63% of corn yield variation for a dry year, but only 22% of yield variation for a favorable weather year (Gantzer and McCarty, 1987). Reduction in crop yield with shallow claypan topsoil has been attributed to a root-zone that is less than ideal for root growth (Scrivner et al., 1985a).

The influence of topsoil thickness on crop growth and yield is caused by markedly different soil chemical and physical properties between the topsoil and soil within the claypan. Specific soil factors that contribute to yield reduction when claypan topsoil is shallow are: (i) a decrease in root-zone plant-available water capacity (Gantzer and McCarty, 1987; Thompson et al., 1991; USDA-NRCS, 1995); (ii) clay accumulation and poor soil structure within the Bt horizon that restrict root penetration (Jamison et al., 1968; USDA-NRCS, 1995); and (iii) low soil organic matter, fertility, and early-season oxygen levels conducive for root growth (Jamison et al., 1968). These well understood soil and plant relationships provide a basis for interpreting claypan soil topsoil thickness as the effective rooting zone for crop plants. Thus claypan soil topsoil thickness is used in this research report as a measure of root-zone suitability for crop growth.

Measuring within-field variations in root-zone characteristics affecting crop growth would assist producers and crop consultants in developing site-specific management strategies. The objective of this research was to evaluate claypan soil EC_a with topsoil thickness and within-field variability of grain crop production.

MATERIALS AND METHODS

Sites Description

Research sites included four claypan soil fields (CF) located within MLRA 113 (Soil Survey Staff, 1981) of north-central Missouri. Fields 1 through 3 are located within 3 mi of Centralia, MO, and Field 4 is located within 1 mi of Novelty, MO. Table 1 provides field size, soil association, and cropping history information for the research years.

Soil Electrical Conductivity Measurements

Soil EC_a for each field was measured on a single date (Table 2) using the EM38[1] (Geonics Ltd., Mississauga, Ontario, Canada). The EM38 is a lightweight bar approximately 3 ft in length and includes calibration controls and a digital readout of EC_a in milliSiemens per meter (mS/m). An analog output port is provided to allow data to be recorded on a data logger or computer. The instrument was operated in the vertical dipole mode, providing an effective measurement depth of approximately 5 ft (McNeil, 1992), which is well suited for focusing on the depth of the root-zone of annual grain crops. The instrument response to soil conductivity varies as a nonlinear function of depth. As weighted by the instrument response, signal strength peaks at a dis-

[1] Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the United States Department of Agriculture.

Table 2. Calibration dataset statistics and linear regression equations relating $1/EC_a$ to claypan soil topsoil thickness† for four claypan soil fields.

Field	Date of soil EC_a survey	n	Minimum topsoil	Maximum topsoil	Equation‡	Standard error	r^2
			in.			in.	
CF1	24 Nov 1997	21	2.1	53.6	$y = -65.2 + 3409.1x$	7.0	0.76
CF2	30 Nov 1995	16	5.1	45.3	$y = -30.0 + 1428.3x$	3.7	0.89
CF3	2 Apr 1997	19	0.8	37.5	$y = -28.4 + 1990.3x$	4.0	0.84
CF4	18 Apr 1997	15	2.0	15.5	$y = -19.8 + 1389.7x$	3.6	0.44

† Topsoil thickness defined here as the depth of soil to the first Bt horizon.
‡ y = topsoil depth in inches, $x = 1/EC_a$ as measured by EM sensing.

tance 16 in. below the instrument and then decreases with depth (Geonics Limited, 1998).

Collection of EC_a data was accomplished with a mobile EM38 measurement system that included an all-terrain vehicle, a wooden trailer carrying the EM38 meter 6 in. above the ground, a differentially corrected (within 10 ft of actual) GPS receiver, and a computer for data acquisition (Kitchen et al., 1996). Data were collected on transects approximately 66 ft apart over the fields. Data were recorded on a 1-s interval, corresponding to a measurement every 6 to 9 ft along the measurement transects, giving approximately 70 to 100 EC_a readings per acre.

On the same day that EC_a measurements were taken, 15 to 21 calibration data points selected to span the range of EC_a values encountered in each field were soil sampled with a hand probe and the depth of the upper boundary of the Bt horizon (i.e., the claypan depth) was determined. This soil depth was referred to as "topsoil thickness" in this research. Apparent soil electrical conductivity measurements were taken with the mobile EM system at these same calibration points. A regression equation relating EC_a to topsoil thickness was determined for each field. Lesch et al. (1995) advocated the use of a similar "regression model/groundtruthing technique" when the major factor(s) affecting EC_a measurements were known and when the within-field variability in other factors affecting EC_a was low to moderate.

Our experience on claypan soils has shown that clay content and depth of the highly conductive Bt horizon are the major factors influencing within-field variations in EC_a (Doolittle et al., 1994; Sudduth et al., 1995). In general, EM sensing of EC_a can be affected by a number of different soil properties including clay content, soil water content, varying depths of conductive soil layers, temperature, salinity, organic compounds, and metals (Geonics Limited, 1992, 1997). Of these potential influencing constituents, salinity and metals are not significant in the claypan soil area. At a single measurement date, soil temperature should be relatively constant on these generally flat fields, where differences in slope and aspect are not large enough to cause significant differences in solar heating. Within-field variations in soil moisture content could affect EC_a readings, so EM surveys were conducted in the late fall or spring (Table 2) when the soil profile was at or near field capacity to minimize differences in profile soil moisture. At these times of measurement, any differences in profile soil moisture content would most likely be due to soil texture differences. Since fine-textured soils have a higher moisture content at field capacity than coarser-textured soils and both characteristics result in greater EC_a, this effect should increase the sensitivity of EC_a measurements to profile-weighted clay content and topsoil thickness. With this procedure, although absolute EC_a readings may vary, similar values of EC_a- estimated topsoil thickness can be reproduced on claypan soils from another set of mobile EM and calibration data collected at a different time and under different conditions (unpublished data).

Soil Nutrients and Yield Data Collection

Fields were grid soil-sampled to a 6 in. depth and analyzed for P (Bray 1 extractable), K, Ca, Mg (ammonium acetate extractable), CEC (sum of bases), organic matter (wet oxidation), salt pH, and neutralizable acidity (Woodruff buffer method) using standard University of Missouri procedures (Brown and Rodriguez, 1983). Grid spacing was 100 ft for Field 1, 82 ft for Fields 2 and 3, and 108 ft for Field 4. Gleaner R42 (15 ft header) or R62 (20 ft header) combines (AGCO Corp., Duluth, GA) equipped with Ag Leader Yield Monitor 2000 (At Leader Technology, Ames, IA) yield sensing systems were used to obtain data for yield maps. Yield data collection and processing techniques were described by Birrell et al. (1996).

Data Analysis

Yield and EC_a data were processed using geostatistics, and appropriate semi-variogram models and parameters were used to krige the data to a grid with a 33-ft cell size. To avoid problems associated with interpolation of sparse data, a data set for examining the effects of soil nutrients was created by selecting the yield data from the 33-ft grid cell nearest the grid soil-sample data points, along with the actual soil nutrient results from those points. Cells where yield data was questionable because of end rows or harvesting problems were removed. Correlations between yield and soil data were calculated.

Boundary Line Analysis

More complete datasets of yield and EC_a were obtained from the mapped data, using common 33-ft grid cells over the entire mapped fields. Questionable yield points were again removed. The relationship between yield and EC_a on these datasets was explored using the concepts of an upper "boundary line." This procedure, detailed by Webb (1972), selects a subset of points from the original data that are the "best performing" in terms of some response variable (e.g., yield). Typically with this analysis either a line is drawn or an equation fit to this subset of points lying on the upper edge of the data (hence the name "boundary line") when viewed in a two-dimensional scatter plot. This upper boundary then represents, for the conditions of that data set, the maximum possible response to that limiting factor (e.g., EC_a), and points below the boundary line represent conditions where other factors have limited the response variable. The boundary line analysis rests on the supposition that there are limits in response to factors or treatments in any situation (Webb, 1972). The boundary line procedure has been used in a number of plant and soil studies including strawberry (*Fragaria* spp.) weight as influenced by achene

Table 3. Correlation coefficients (r) between grain yield and soil parameters.

Field	Year	Crop	n†	pH(salt)	Neutralizable acidity	Soil OM	P	Ca	Mg	K	CEC	Soil EC_a
CF1	1993	corn	318	0.07	–0.16*	0.05	–0.08	–0.04	–0.17*	–0.01	–0.15*	–0.13*
	1994	soybean	344	0.13*	–0.13*	–0.14*	0.08	–0.08	– 0.12*	–0.05	–0.16*	–0.20*
	1995	sorghum	301	0.05	–0.01	0.16*	0.06	–0.07	–0.05	–0.02	–0.06	–0.26*
	1996	soybean	355	–0.11*	0.11*	0.22*	0.01	0.12*	0.17*	0.13*	0.18*	0.06
	1997	corn	336	0.08	–0.01	0.09	0.27*	0.03	0.06	0.13*	0.03	– 0.45*
CF2	1995	soybean	436	–0.11*	–0.08	–0.41*	0.04	–0.51*	–0.41*	–0.35*	–0.45*	–0.07
	1996	corn	429	0.01	–0.08	–0.27*	0.27*	–0.32*	–0.25*	–0.18*	–0.28*	–0.12*
	1997	soybean	420	–0.03	–0.12*	–0.31*	0.03	–0.33*	–0.27*	–0.27*	–0.32*	–0.17*
CF3	1996	soybean	189	0.01	0.12	0.33*	–0.42*	0.28*	0.31*	0.25*	0.31*	0.20*
	1997	corn	186	–0.12	0.05	–0.34*	0.03	–0.61*	–0.70*	–0.70*	–0.64*	–0.67*
CF4	1995	soybean	69	–0.18	0.16	0.60*	0.16	0.07	0.08	0.48*	0.19	–0.36*
	1996	corn	83	0.08	–0.10	0.24*	0.52*	–0.23*	–0.30*	0.39*	–0.26*	–0.10
	1997	soybean	73	–0.07	0.03	0.38*	0.11	–0.17	–0.35*	0.22	–0.15	–0.43

** Significant (test for $|r| = 0$) at $P \leq 0.05$ level.
† Number of data points.

number (Abbott et al., 1970); soil properties affecting denitrification rates (Bergstrom and Beauchamp, 1993; Elliott and de Jong, 1993); environmental control of leaf stomatal conductance (Livingston and Black, 1987; White et al., 1999); and crop yield response to pH and other soil fertility factors (Nielsen and Friis-Nielsen, 1976; Walworth et al., 1986; Evanylo and Sumner, 1987). A computer program has been developed that automates the boundary line procedure (Schnug et al., 1996).

Boundary line analysis works best when data sets are large (such as with spatially dense data obtained from combine yield monitoring). The boundary line analysis procedure assumes there is a significant biological response between the potential limiting factor and the response variable in order to imply the cause-and-effect relationship (Webb, 1972; Lark, 1997). A weakness of the analysis is that it is a single factor analysis, like simple correlation, and assumes insignificant joint effects with other factors at the boundary (Lark, 1997). Webb (1972) asserted that boundary line analysis is a procedure for exploring response relationships for the purpose of indicating "where attention should be directed for the greatest prospect of increasing yield." For this analysis we recognize that EC_a per se is not a direct measure of a yield-limiting factor. However, it is an estimate of topsoil thickness which, as previously discussed, affects numerous soil properties that mediate crop growth.

Using boundary line analysis for examining the relationship of yield to EC_a, the "upper edge" of data for our boundary line was determined as follows. Ordered EC_a values, from lowest to highest, were divided into N/100 increments (where N = number of paired yield-EC_a measurements for a site-year) and processed so that each EC_a increment contained an equal number (approximately N/100) of paired yield-EC_a measurements. For each increment, data above the 95th percentile of yield was selected to represent the upper edge and included in a data subset. Based upon preliminary investigations, a log-normal peak function was chosen to fit the boundary data subset and generate a boundary line. The log-normal peak function was flexible in representing various response combinations to EC_a values. This data selection procedure for the boundary line was chosen because the density of data varied over the EC_a range (with data generally sparse at relatively low and high EC_a measurements), thus diminishing bias for data selection at low and high EC_a values. This boundary procedure did not test for and exclude outlier data, nor did it envelop the remaining data with the boundary line as others have done (Schnug et al., 1996).

The log-normal peak function is as follows:

$$y = a + be^{-0.5[\ln(x/c)/d]^2} \quad [1]$$

where, y is yield, x is EC_a, a is the lower limit of yield, b is the height of the peak above a, c is the value of x over which the peak is centered, d is a curve-fitting parameter giving shape and width to the peak, and e is the base of natural (or Napierian) logarithms. For each log-normal equation an adjusted r^2 value was calculated.

RESULTS AND DISCUSSION

Correlation of Grain Yield and Soil Measurements

Correlation coefficients (r) between yield and soil measurements (Table 3) were generally low, even though most correlation coefficients greater than 0.20 were found to be significant (test for $|r| = 0$, $P \leq 0.05$ level). Correlations were generally inconsistent between fields and when comparing the yield from relative low (e.g., CF1 1994) and high (e.g., CF1 1996) precipitation years. Yield and soil measurement correlations for CF1 were low for all crop years. Claypan Field 2 exhibited the most consistent trend with negative and somewhat significant correlation coefficients (ranging from –0.18 to –0.51) for soil organic matter and soil cations. Correlations observed for CF3 in 1997 were similar to CF2 with negative correlation to soil cations as great as –0.70, but CF3 exhibited positive correlations between 1996 soybean yield and soil cations. Correlations between yield and soil organic matter, P, and K were positive for all three crop years on CF4. Correlations between yield and EC_a were mostly negative and low.

Analysis of field-scale yield data using correlation coefficients is usually insufficient for explaining yield variation, but as a first step this approach can be instructive. For example, the trend of negative correlations observed between yield and cations over 3 yr for Field 2 deserves further investigation. Yet, correlations provide little direct evidence for the cause(s) of yield variation. It is difficult to explain why higher soil organic matter on Field 2 would reduce yield within the range of soil organic matter measured on this field. Another limitation of correlation analysis is that it is an assessment of the linear relationship between variables.

If nonlinear relationships exist between yield and yield-limiting factors, correlation analysis may miss important relationships. Additionally, when dealing with entire production fields on the scale of tens of acres, as this study does, multiple and interacting yield-limiting factors are likely (Sudduth et al., 1996). Correlation analysis ignores the multiple factors and interactions present in field-scale investigations. When determining the effect of a single factor on yield, another approach to data analysis is needed to appropriately isolate the effect of the factor under study.

Soil EC_a as a Measure of Topsoil Thickness

Transformed EC_a ($1/EC_a$) was regressed to topsoil thickness for each of these four fields (Table 2), similar to earlier work (Doolittle et al., 1994). Figures 1 through 4 display

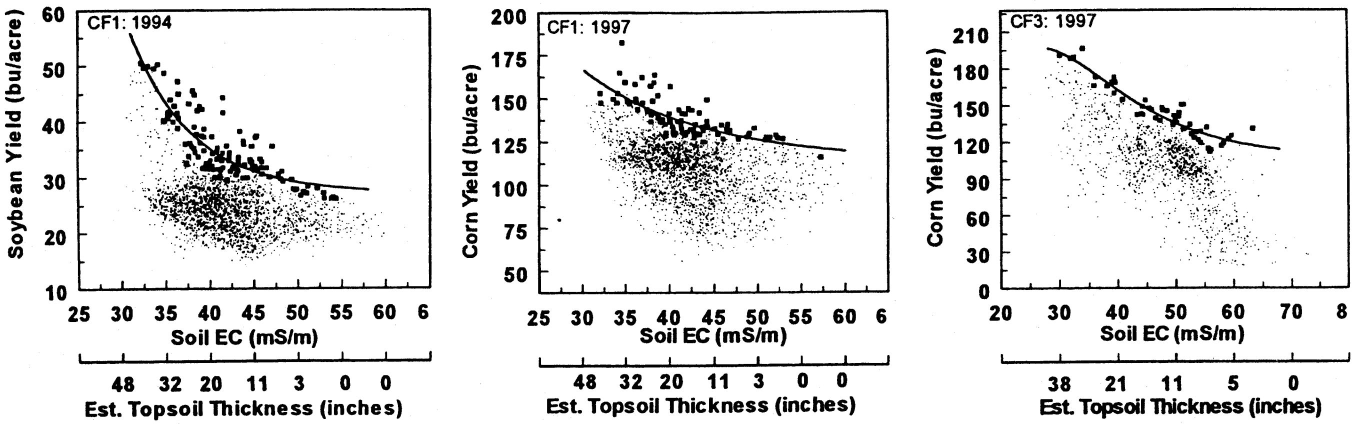

Fig. 1. Scatter plots of EC_a and yield, where yield increased with decreasing EC_a (Condition 1, meaning root-zone suitability improved with decreasing EC_a or increasing topsoil thickness).

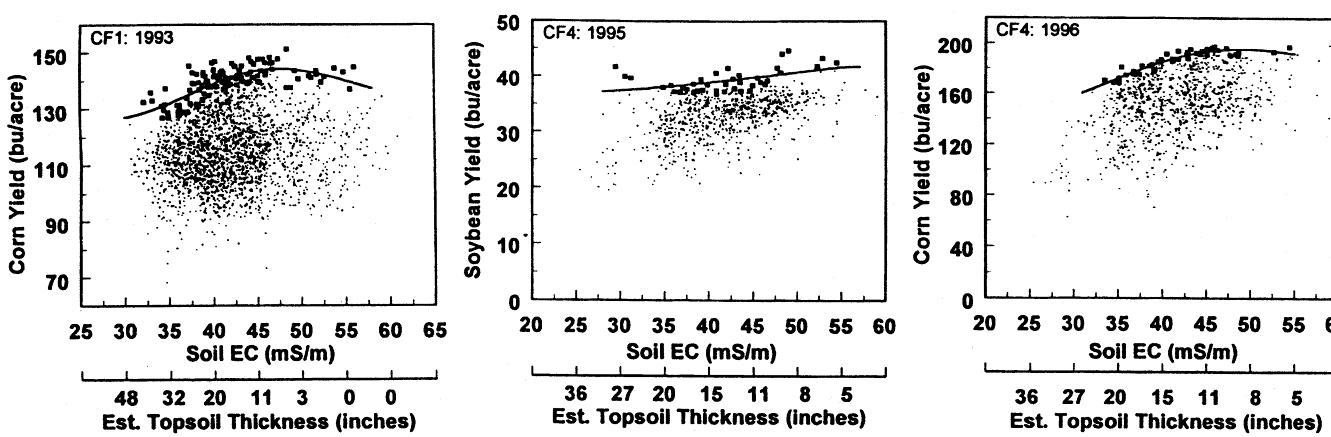

Fig. 2. Scatter plots of EC_a and yield, where yield decreased with decreasing EC_a (Condition 2, meaning root-zone suitability diminished with decreasing EC_a,or increasing topsoil thickness).

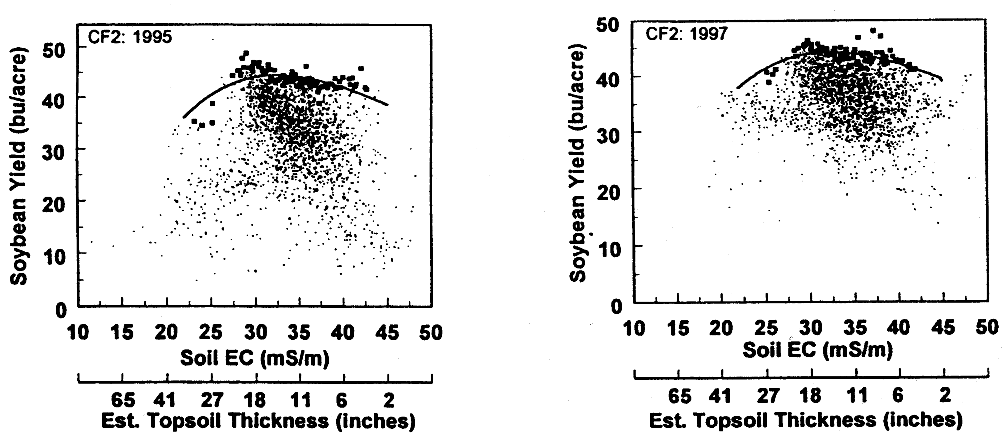

Fig. 3. Scatter plots of EC_a and yield, where yield was less at low and high EC_a values and higher at some mid-range of EC_a (Condition 3, meaning root-zone suitability was best at some mid- range EC_a).

plots of each site-year of grain yield in relation to EC_a, and the estimated topsoil thickness from the Table 2 regression equations are shown as a second x axis. Regression-estimated negative topsoil thicknesses were changed to 0. (The reason for categorizing site-years into different figures is explained later.) Topsoil thickness varied from less than 1 in. to more than 50 in. Claypan Fields (CF) 1 through 3 were located near each other and had a greater range in topsoil variation and higher r^2 values than CF4. Soils on CF4 varied considerably from those found on CFs 1 through 3. While CFs 1 through 3 were gently sloping and entirely classified using Mexico-Putnam claypan association soils, CF4 was gently to moderately sloping and was partly classified with "non-claypan" soils (Table 1). Claypan Field 4 was located near the northern edge of the claypan soil area (MLRA 113) of Missouri in a transitional area between claypan, deep loess, and glacial drift soils.

Developing the Relationship of Yield to Claypan Soil EC_a

The influence of topsoil thickness on crop growth and yield is caused by markedly different soil chemical and physical properties between the topsoil and soil within the claypan. Compared with a soil with deeper topsoil thickness, a shallow topsoil has less plant-available water capacity (Thompson et al., 1991; USDA-NRCS, 1995), greater clay accumulation, and poor soil structure within the Bt horizon that restricts root penetration (Jamison et al., 1968; USDA-NRCS, 1995), and is lower in soil organic matter, fertility, and early-season oxygen levels conducive for root growth (Jamison et al., 1968). Therefore, topsoil thickness is a measure of the effective rooting zone for crop plants. Thus, EC_a as a measure of claypan soil topsoil thickness reflects root-zone suitability for crop growth.

Because of this relationship between topsoil thickness and soil properties affecting root-zone suitability, we hypothesized potential theoretical relationships between EC_a and crop productivity (Fig. 5). High EC_a on claypan soils is associated with thin topsoil and potential yield may be depressed. Potential yield will increase with relatively lower EC_a that is associated with a deeper or nonexistent claypan (Fig. 5, plot a). However, in other investigations (Fraisse et al., 1999) we have shown that low EC_a measurements can be also associated with foot-slope or alluvial areas of the landscape where, in some years, excessive water from runoff accumulation and seepage may hurt crop growth and yield (e.g., early season stand loss or N loss from denitrification). To account for this scenario, a second theoretical relationship between EC_a and crop productivity was hypothesized for years when soil or landscape water was excessive (Fig. 5, plot b). Two additional scenarios were suspected. Plot c of Fig. 5 represents the case when both low and high EC_a values are associated with a decrease

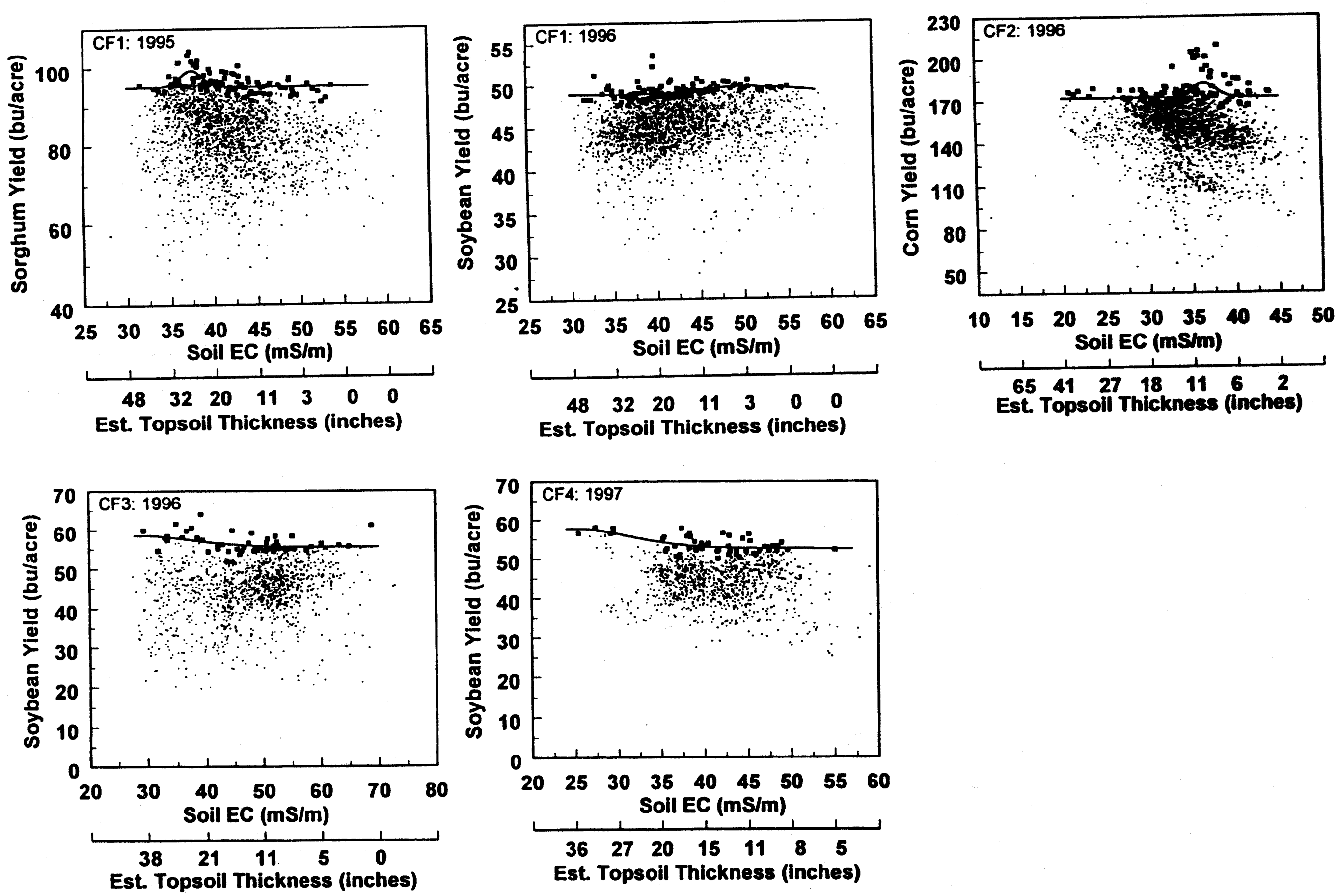

Fig. 4. Scatter plots of yield and EC_a, where yield variation was mostly unrelated to EC_a (Condition 4, meaning root-zone suitability as measured by EC_a had little relationship to yield).

in productivity. A fourth scenario was when there was no evidence of a relationship between EC_a and crop yield (Fig. 5, plot d).

The relationship of EC_a to potential yield was explored using boundary line analysis. While EC_a does not provide a direct measurement of a yield-limiting factor, we proposed that the generally strong relationship between EC_a and claypan-soil topsoil thickness (Table 2) meant that the measurement could be used to delineate soil variations at a field scale associated with root-zone suitability (e.g., soil water storage, potential rooting restrictions, fertility, etc.).

For the 13 site-years evaluated, EC_a and yield data were well dispersed as shown in scatter plots (Fig. 1–4). In some cases, the data was so dispersed that it visually appeared as though there was little or no relationship between EC_a and yield (e.g., Fig. 2, CF1 1993; Fig. 3, CF2 1995). To illustrate how our boundary line technique characterized the relationship between EC_a and yield along the upper edge of data, an artificial dataset was constructed by manipulating the data for the CF1 1993 site-year (Fig. 2, CF1 1993). To remove any correlation between EC_a and yield, EC_a values were randomly assigned to the yield data and a boundary line determined. Figure 6 is the scatter plot and resultant boundary line for this randomized dataset (data selected for boundary line shown as larger points). Visually, it is difficult to see a relationship between EC_a and yield for either figure. Nevertheless, the log-normal boundary line identified a significant relationship between EC_a and yield as shown in Fig. 2, CF1 1993 ($r^2 = 0.55$), but failed to find such a relationship for the randomly assigned data of Fig. 6 ($r^2 = 0.01$).

Interpreting the Relationship of Yield to Soil EC_a

The log-normal regression boundary line for each site-year along with the data used to create the boundary lines (larger points) are shown in the scatter plots of Fig. 1 through 4, and regression parameters are given in Table 4. The log-normal function fit the upper boundary of EC_a and yield data with $r^2 > 0.25$ in nine out of 13 site-years (Table 4). Generally, those site- years with low r^2 values also exhibited relatively small changes in yield over the observed range of EC_a. The boundary line represents the potential yield at given EC_a measurements. Because the data used in this analysis are taken from various crops, sites, and climate years, comparison between site-years requires caution.

Table 4. Boundary line regression parameters and statistics for four claypan soil fields.

Claypan field	Year	Crop	N†	n‡	a	b	c	d	r^2
					log-normal equation parameters (see Eq. 1)				
CF1	1993	corn	2531	125	125	19	47.4	0.212	0.54
	1994	soybean	2603	130	27	318	10.5	0.494	0.69
	1995	sorghum	2218	110	95	4	37.4	0.035	0.30
	1996	soybean	2713	135	49	1	50.1	0.114	0.10
	1997	corn	2570	105	113	183	9.8	0.727	0.54
CF2	1995	soybean	2692	108	–4	49	32.6	0.638	0.31
	1996	corn	2637	130	172	10	36.4	0.038	0.13
	1997	soybean	2587	104	–4	48	32.3	0.717	0.29
CF3	1996	soybean	1308	60	56	3	29.5	0.245	0.12
	1997	corn	1240	52	106	91	26.3	0.424	0.87
CF4	1995	soybean	809	46	35	45	603.5	1.223	0.20
	1996	corn	973	48	144	51	49.0	0.302	0.88
	1997	soybean	1103	55	52	5	25.4	0.215	0.28

† Total number of data points.
‡ Data points used for log-normal curve fitting.

Each of the 13 site-years of this investigation was associated with one of the four condition categories, (conditions shown in Fig. 5) and are grouped as such in Fig. 1 through 4. Significance of variation in a boundary line was determined by comparing the change in yield value along the boundary line over the range of measured EC_a to the standard deviation of yield for each site-year. When the change in yield along the boundary line was greater than one standard deviation of the yield data set, either to the right or left of the log-normal peak, site-years were placed in Condition 1 (Fig. 1) or Condition 2 (Fig. 2) categories, respectively. Site-years showing a change in yield along the boundary line greater than one standard deviation on both the right and the left sides of the log-normal peak were placed in Condition 3 (Fig. 3). When the change in yield along the boundary line was less than one standard deviation of the yield dataset, site-years were placed in Condition 4 (Fig. 4).

Three observations help explain why the results are variable and fall into these condition categories. One, for these

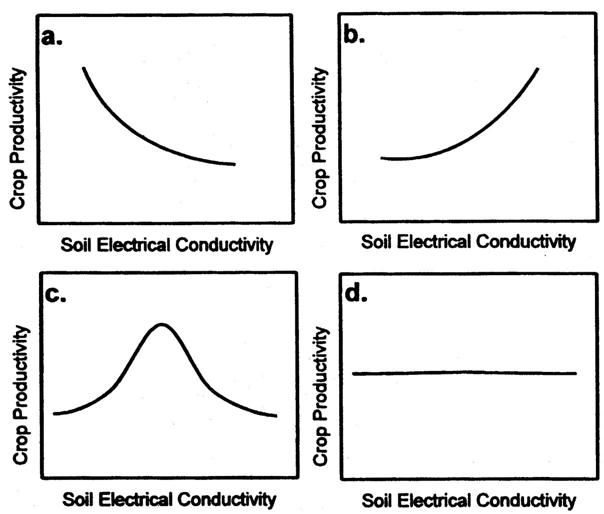

Fig. 5. Four plots that illustrate how crop grain yield maybe related to EC_a on claypan soils.

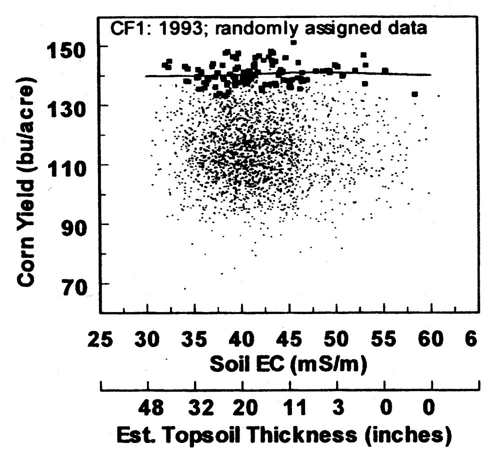

Fig. 6. Scatter plot and boundary line of EC_a and yield for CF1 1993 with EC_a randomly assigned to yield data.

poorly drained claypan soils frequent early season rainfall often gave a poor seedbed for crop establishment and stand, a condition that can suppress final grain yield. Two, adequate and timely precipitation during flowering and seed fill (for these sites, mid July through mid September) is crucial for grain production. Crop water stress can occur even when rainfall is similar to long-term average rainfall for this section of the Corn Belt because of the droughty nature of these soils. Average monthly precipitation for this claypan soil region is between 3.5 and 4.0 in. for July and August (Shaw et al., 1960). Three, the crops reported in this study respond differently to water stress.

Condition 1 Site-Years. Three site-years showed increasing potential yield with decreasing EC_a for the boundary line data (Fig. 1). In each of these site-years plant stress due to deficient plant-available water during the crucial periods of flowering and seed fill was observed. For the site-year in soybean (Fig. 1, CF1 1994) precipitation was well below normal for both July and August (Fig. 7, plot a) resulting in aborted flowers and fewer beans per pod than normal (recorded in field notes, not measured). For the two corn site-years (Fig. 1, CF1 1997, CF3 1997) July rainfall was very low and plants were water stressed during pollination in many areas of the field. Concurrently, some areas of the fields did not visually show water stress. In a separate study on CF1 in 1997, remaining plant-available water at pollination varied from less than 3 in. to more than 12 in. in the top 4 ft of soil and was positively related to EC_a-derived topsoil thickness ($r^2 = 0.87$; Spautz, 1998). Stand was not observed to be a problem for these site-years. (The cover of this journal issue shows the soil EC_a map, aerial photo at pollination, and yield map corresponding to Fig. 1:CF 3 1997 data.)

Condition 2 Site-Years. Three site-years exhibited decreases in potential yield with decreasing EC_a for the boundary line data (Fig. 2). Two of these (CF1 1993 and CF4 1996) visually expressed a yield peak (optimal yield) relative to EC_a, but the peak was relatively small and not significant according to our classification criteria. Heavy and consistent spring and summer rainfall in 1993 saturated soils through much of the growing season. The excessive rainfall reduced crop stand on CF1 in low-lying areas of the field and produced chlorotic leaves by mid-July (recorded in field notes, not measured), suggesting N loss to either denitrification or leaching. Plant disease incidence was also unusually high. Areas of low EC_a were most notably affected by these conditions, helping to explain decreased yield in these areas.

As discussed previously, CF4 has a mixture of claypan (typically at summit and shoulder landscape positions) and non-claypan soils (typically at side and footslope landscape positions). Lower EC_a generally corresponded with the non-claypan soils. For CF4 in 1995 an unusually wet May, July, and August (Fig. 7, plot b) depressed soybean yield, particularly on areas with lower EC_a. Reduced stand and plant diseases were attributed as the probable causes of yield reduction in these relative low-elevation areas of the landscape where runoff accumulated. For CF4 in 1996, July rainfall

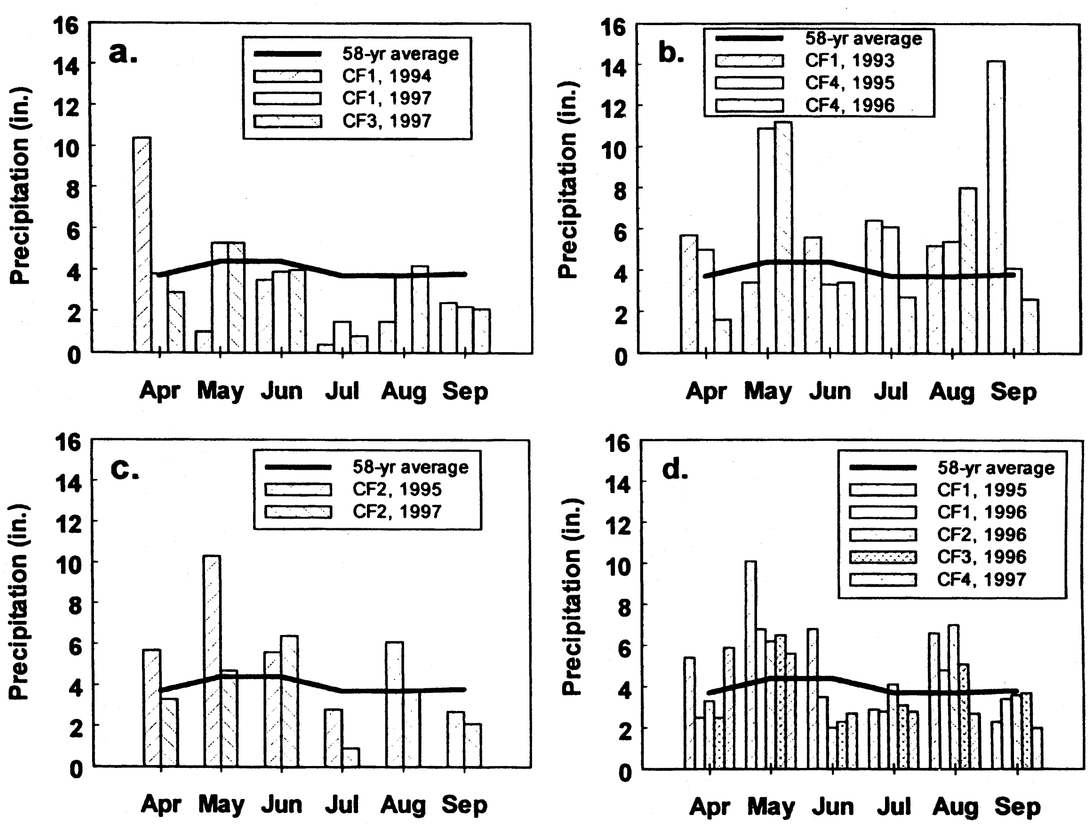

Fig. 7. Monthly growing-season precipitation for each site-year compared with long-term average precipitation, and categorized by the conditions illustrated in Fig. 5.

was well below average, causing water stress to the corn crop, especially in low EC_a areas of the field where better surface drainage resulted in drier soils.

Condition 3 Site-Years. Two of the three site-years of CF2 gave boundary line results where depressed potential yield was associated with both low and high EC_a values (Fig. 3). Both site-years were wet early in the growing season (Fig. 7, plot c). Most low EC_a areas on CF2 were associated with a low-elevation area of the field where runoff water ponds and slowly drains through a culvert under a state highway. For both of these site-years, stand was reduced in this low EC_a area (recorded in field notes, not measured), the probable cause for depressed yield at low EC_a. Yield was also depressed at high EC_a values.

Condition 4 Site-Years. Five site-years had relatively flat boundary lines, indicating little or no association between EC_a and potential yield variation (Fig. 4) . The implication relative to the theoretical relationship of EC_a (Fig. 5, plot d) is that conditions were approximately "optimal" over the range of EC_a values. An examination of the crop type and rainfall helps explain why these site-years fall into Condition 4. Rainfall for July and August for these site-years was near or above average (Fig. 7, plot d). Of these five site-years, three were in soybean, one was in corn, and one was in grain sorghum. Soybean tolerates short periods of water stress during flowering and seed fill well because of its indeterminate flowering. Soybean yield components are determined over 6 to 8 wk (Raper and Kramer, 1987). In contrast, corn is particularly sensitive to droughty conditions, especially during the 5 to 7 d of pollination that can cause substantial yield loss (Shaw, 1988). Previous work on claypan soils has shown corn to be more than five times more sensitive to topsoil thickness and water deficiency than soybean (Thompson et al., 1991). The one corn site-year fitting Condition 4 (Fig. 4, CF2 1996) had more than 11 in. of rainfall during July and August. Grain sorghum is also very drought tolerant with more year-to-year yield stability for the claypan soil region (Fischer, 1989). No significant crop stand problems or water stress were noted for these five site-years.

Soil EC_a as a Claypan-Soil Productivity Measure

The dispersed nature of the data in the 13 scatter plots is indicative of the multiple yield-controlling factors that will inevitably be observed when examining crop production data collected over large areas. Root-zone suitability in the general sense is a composite of many measurable properties, much more than what topsoil thickness or EC_a can represent. Soil EC_a is only a partial indicator of that suitability. The primary value of EC_a as examined using boundary line analysis as a diagnostic tool for delineating possible soil problems associated with topsoil depth and to estimate the magnitude of yield loss due to less than ideal root-zone physical conditions. It does not help identify specific potential corrective measures for the soil.

While the boundary line analysis did show significant relationships between EC_a and grain yield in a majority of site-years, interpretation of the relationship was aided by information on (in order of importance) within-season rainfall, crop type, and specific field characteristics. Each of the four fields gave boundary line results classified in two or more condition categories. Excessive early-season rainfall was noted to have reduced crop stand in areas where EC_a was low (also areas of low relative elevation) and consequently depressed grain yield (Fig. 2, CF1 1993; Fig. 3). For one area of CF2 where EC_a was low, grain yield would probably be increased if surface water drainage improvements were made. The relationship between EC_a and yield was most dramatic when crops were stressed with droughty conditions. For corn, adequate rainfall during grain fill could not compensate for water stress during pollination (Fig, 1, CF1 1997; CF3 1997). Soybean yield was generally more stable relative to high EC_a unless dry conditions prevailed during flowering and seed filling (Fig. 1, CF1 1994).

How might producers use an understanding of the relationship between EC_a and grain yield for improved management? Thirteen claypan soil site-years of data have allowed us to begin using spatially dense EC_a measurements in concert with yield monitored data. The interpretation of these data increase our understanding of the potential effect these soil physical conditions that influence EC_a measurements control yield, and with a sound understanding of soil influence on crops, give direction for improved site-specific management.

Without irrigation, improvement to droughty, high EC_a soil areas (low topsoil thickness) is limited to either management that can increase water infiltration and water conservation (e.g., conservation tillage methods) or the planting of more drought-tolerant crops (e.g., soybean or grain sorghum). Management options seem more feasible for soil areas where low EC_a may also be associated with low elevation and potential excessive water. As discussed, production in an area of low EC_a on CF2 could benefit by improving surface drainage, but certainly a toposurvey of the field, rather than EC_a, would be a more relevant measurement for making corrections to surface drainage problems. Subsurface tile lines are uncommon on claypan soils because the claypan causes poor internal drainage, but areas of low EC_a where the claypan horizon is deeper, could potentially be suitable for tile drainage. These areas are often wet, needing drainage, and have better internal drainage because of greater topsoil thickness.

Nitrogen fertilization rates for corn are often determined using an expected yield value. With the exception of CF1 with 2 yr of corn, only 1 yr of corn production data was available for each site. With these data there is no consistent corn productivity trend associated with EC_a. Without knowledge of cropping season precipitation, predicting grain yield and crop N needs using EC_a will be difficult. Further research has been initiated to explore variable-rate N fertilization based upon EC_a.

A significant potential use of yield and EC_a data is in improving the ability to assess other potential yield-limiting factors. For example, after dividing claypan fields into subfields using EC_a and relative elevation, correlation coefficients between yield and soil test data (e.g., soil-test pH, P, K, Mg, and Ca) were greatly improved over correlations performed on a whole-field basis (Sudduth et al., 1996).

CONCLUSIONS

Soil EC_a provided an estimate of the within-field soil differences associated with topsoil thickness, and which for these claypan soils, is a measure of root-zone suitability for crop growth and yield. Significant relationships between potential grain yield and EC_a were shown using a form of boundary line analysis, but climate, crop type, and specific field characterization information were required to help explain the relationship for any given site-year. Use of the boundary line analysis EC_a helped to delineate the magnitude of potential yield loss due to less than ideal conditions in the root-zone. Because EC_a measurements were a good estimate of topsoil thickness, EC_a may be used to diagnose potential rooting and water-related problems affecting grain crop production. For these claypan soil fields, the analysis pointed to a few specific management options that could be considered for each field.

The scatter in the data of this study illustrate how EC_a alone can not be used to accurately predict crop productivity variation. Many other layers of information are needed (e.g., insects, weeds, diseases, fertility, crop stand, topograhphy) for both yield map interpretation and management planning. Yield maps have reinforced producers' and researchers' understanding that soil and landscape features usually are the most influential factor causing within-field variability in grain crop production. Producers struggling to understand the variability seen in yield maps probably will observe trends between yield and EC_a before observing relationships between yield and some other factors (e.g., soil-test P or K). The credibility and future adoption of precision farming strategies will be conditional on a producer's ability to measure, interpret, and predict soil and landscape properties that help explain their impact on grain crop production. Soil EC_a helped provide a measure of root-zone suitability for crop productivity of claypan soils.

Use of EC_a for variable-rate applications of fertilizer, seed, and pesticides may have potential and warrants additional investigation. However, more reliable long-term forecasting of rainfall may be necessary in order to predict outcomes and develop the best prescription.

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