Relationship of Apparent Soil Electrical Conductivity to Claypan Soil Properties

W. K. Jung, N. R. Kitchen,* K. A. Sudduth, R. J. Kremer, and P. P. Motavalli

ABSTRACT

Understanding relationships between sensor-based measurements and soil properties related to soil quality may help in developing site-specific management. The primary objective of this research was to examine whether sensor-based apparent soil electrical conductivity (EC_a) could be used to predict soil properties for claypan soil. Soil samples were obtained at three depths intervals (0- to 7.5-, 7.5- to 15-, and 15- to 30-cm depths) at 65 locations within a 4-ha area of an agricultural field located in north central Missouri in 2002. Samples were analyzed for numerous physical, chemical, and microbiological properties that serve as soil quality indicators. The EC_a measurements were also collected at the coring locations with an electromagnetic induction-based sensor. A combine equipped with a commercial yield-sensing, GPS based recording system was used to map corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] yields from 1993 to 2002. At the deepest sampling depth, soil bulk density (D_b), clay, silt, cation exchange capacity (CEC), and Bray-1 P were the most significantly correlated ($r > 0.55$) with EC_a. Soil properties were regressed against EC_a, and R^2 values were often improved using a quadratic term of EC_a, especially at the 0- to 7.5-cm depth. Selected regression models were validated with an independent soil sample data set ($n = 20$). Soil properties were similar between measured and predicted. Some soil properties (e.g., clay and CEC) and EC_a that were positively correlated to yield in years with average or greater than average cumulative July to August precipitation (>15 cm) were negatively correlated to yield for years with less than average precipitation (<15 cm). Our results suggest that sensor-based EC_a can be a quick and economical way of estimating some claypan soil quality measurements.

Quantitative assessments of soil quality are required to evaluate practices for sustainability related to agricultural production (Doran and Parkin, 1994). The concept of soil quality is complicated by the many definitions applied, but common characteristics of these definitions are an evaluation of the state of the soil to perform agricultural and environmental functions (Doran and Parkin, 1994). Practical assessment of soil quality requires consideration of different soil functions and their temporal and spatial variation (Larson and Pierce, 1994; Kettler et al., 2000).

Larson and Pierce (1994) proposed a minimum data set of indicator measurements to quantify the state of soil quality. Indicator measurements could be combined to produce an overall soil quality index, but more importantly, subsets of indicators could be related to a specific soil function (Karlen and Stott, 1994; Brejda et al., 2000). Indicator measurements used to assess soil quality must be responsive to management practices to observe changes that might either improve or impair the soil (Karlen et al., 1997; Wander and Bollero, 1999). Soil quality indicators could be described into inherent soil properties, those that change slowly over time (e.g., soil texture and hydraulic characteristics), and dynamic soil properties such as those that management can influence (e.g., pH, soil water use from the tillage, and plant nutrient levels). A list of basic soil properties that meet many of the requirements for screening soil quality was developed by Doran and Parkin (1994). A framework for evaluating site-specific changes in soil quality was also developed by Karlen and Stott (1994), where high-quality soil was defined as one that accommodates water entry, retains and supplies water to plants, resists degradation, and supports plant growth.

An evaluation of how various management practices affect soil quality in claypan soils is important because these soils are highly sensitive to soil degradation from processes such as runoff and erosion (Nikiforoff and Drosdoff, 1943; Kitchen et al., 1998). The central claypan soil region occupies about 4 million ha in Missouri and Illinois and is identified as Major Land Resource Area 113 (Soil Survey Staff, 1981). Claypan soils are poorly drained because of a restrictive high-clay subsoil layer usually occurring 20 to 40 cm below the soil surface. However, erosion on claypan soil landscapes can result with the claypan being exposed on some landscape positions (e.g., side slope) and buried to >60 cm in other landscape positions (e.g., toe slope) (Kitchen et al., 1999). The claypan creates a unique hydrology, controlled by a slow water flow in the soil matrix of the restrictive clay layer. Clay content in the argillic horizon is generally >500 g kg^{-1} and is comprised of smectitic (high shrink–swell) clay minerals. During the mid- and late-summer months, claypan soils crack when dry, with maximum soil crack volumes ranging from 0.06 m^3 m^{-3} to 0.17 m^3 m^{-3} (Larson and Allmaras, 1971; Baer et al., 1993). Following summer drying, water flows rapidly through preexisting biopores and cracks, filling them with coarser-textured surface soil. Additional characteristics of claypan soils have been previously reviewed in more detail (Kitchen et al., 1998).

Some soil physical and chemical properties can be estimated from sensor-based measurements. For example, EC_a can provide an indirect indicator of a soil property (Rhoades and Corwin, 1981; Amente et al., 2000; Sudduth et al., 2003). Soil properties that affect EC_a include clay content, soil water content, varying depths of conductive soil layers, temperature, soil salinity, or-

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W.K. Jung and P.P. Motavalli, Dep. of Soil, Environmental and Atmospheric Sciences, 148 Agricultural Engineering Building, and N.R. Kitchen, K.A. Sudduth, and R.J. Kremer, USDA-ARS, Cropping Systems and Water Quality Research Unit, 269 Agricultural Engineering Building, Univ. of Missouri-Columbia, Columbia, MO 65211. Received 21 June 2004. Soil & Water Management & Conservation. *Corresponding author (KitchenN@missouri.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: CEC, cation exchange capacity; D_b, soil bulk density; EC_a, apparent soil electrical conductivity.

ganic compounds, CEC, soil pore size, and metals (McNeill, 1992; Geonics Limited, 1997). Functional relationships between EC_a and soil water content, soil water salinity, and soil properties were initially examined by Rhoades et al. (1976), and a simple capillary model was developed to explain interactions of soil properties and EC_a (Corwin and Lesch, 2003). Mapped EC_a measurements have been significantly correlated with some soil properties taken to a depth of 15 cm from the surface and with yield on claypan soil fields (Kitchen et al., 1999). EC_a provided an estimate of the within-field differences in topsoil thickness of claypan soil (Doolittle et al., 1994), which is a measure of root-zone suitability for crop growth and yield (Kitchen et al., 1999, 2003). Clay content, D_b, pH, and $EC_{1:1}$ sampled to a 30-cm depth was positively correlated with EC_a for a dry-land Colorado field (Johnson et al., 2001). In the same study, soil water content, total and particulate organic matter, total and biomass N, and surface-residue content were negatively correlated with EC_a. In a mid-Atlantic coastal plain study (Anderson-Cook et al., 2002), EC_a was found to be an effective tool for classification of soil types.

Two EC_a sensor types often used in agricultural field investigations are the rolling coulter (Lund et al., 1999) and electromagnetic induction (McNeill, 1992). A coulter-type EC_a sensor has been compared with an electromagnetic-type sensor and found to be similar across different soil types within the U.S. Midwest (Sudduth et al., 2003). The EM38 (Geonics Limited, 1998)[1] is an electromagnetic induction sensor that has been extensively used for field investigations of soil salinity and other properties (Rhoades and Corwin, 1981). It is particularly suitable for rocky, dry, or compacted soils where it is difficult to make good contact with coulter or electrode sensors. Electromagnetic induction sensors are also useful when measuring soil conductivity in vegetative systems where coulter designs may disturb a growing crop. The EM38 is a lightweight bar designed to be carried by hand and provide stationary EC_a readings. The EM38 can be operated in two measurement modes: the vertical dipole mode and horizontal dipole mode, which provide an effective measurement depth of ≈1.5 and ≈0.75 m, respectively. Sensitivity to the near surface in the vertical dipole mode is relatively low but increases with depth, with maximum sensitivity at about 30 to 60 cm. In the horizontal dipole mode, sensitivity is at a maximum at the surface and decreases exponentially with depth (McKenzie et al., 1989; Sudduth et al., 2001). The sensor can also be lifted above the soil surface to change the sensing depth, and in this way has been used to determine depth of different soil layers (Geonics Limited, 1998). Few studies have been conducted to evaluate how the EM38 should be used to assess near-surface soil properties.

Implementation of precision farming or site-specific management concepts for evaluating soil properties has been minimal because of the time, expense, and the perceived lack of direct financial benefit for producers (Kitchen et al., 2002). For example, the cost in 2002 to sample and characterize, by soil horizon, a single 1.2-m-deep soil core with routine laboratory analysis (Columbia, MO) was >$300 (U.S.). If soil properties could be measured quickly and inexpensively, mapping of soil properties within fields would allow critical evaluation of management practices and could lead to site-specific management. The primary objective of this research was to examine whether sensor-based EC_a could be used to predict soil properties of an agriculturally-managed claypan soil. For this research, the emphasis was with soil properties that had some effect on grain crop production. A secondary objective was to evaluate EM38 operating options to find the procedure that provided the best relationships between EC_a and soil properties.

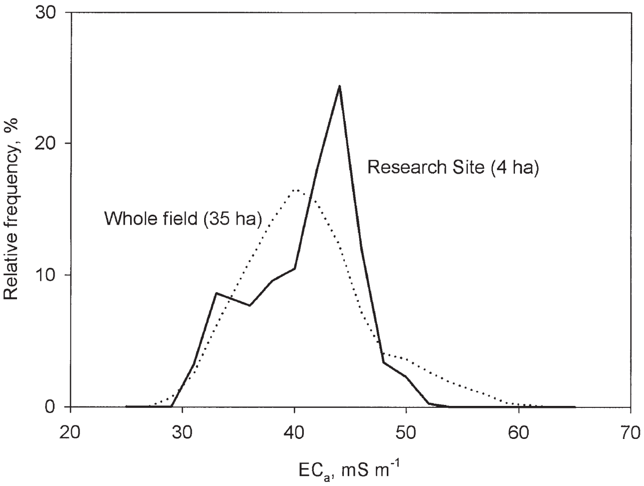

Fig. 1. Histogram of apparent soil electrical conductivity (EC_a) for whole field and research site.

MATERIALS AND METHODS

Study Site

The research site was a 4-ha area within a larger 35-ha field located 3 km north of Centralia, in central Missouri (39°13′48″ N, 92°07′00″ W). A preliminary survey of EC_a over the entire 35-ha field was conducted on a 5-m transect spacing using a mobile EM38 (Geonics Limited, 1998) data acquisition system as described in Kitchen et al. (1999). The 4-ha area selected for this study was chosen to represent the soil and landscape variability that existed for the entire field. Figure 1 shows a histogram of EC_a for the 4-ha area compared with a histogram of EC_a for the whole field.

The soils on the field are of the Adco series (fine, smectitic, mesic Vertic Albaqualfs) and Mexico series (fine, smectitic, mesic Aeric Vertic Epiaqualfs). These soils are very deep, somewhat poorly drained, and very slowly permeable, formed in loess or loess and pedisediment. They occur on uplands and have slopes of 0 to 5%. Surface soil texture ranges from silt loam to silty clay loam. The subsoil claypan horizons are silty clay loam, silty clay, or clay, and commonly contain as much as 50 to 65% clay. Within the 4-ha study area, topsoil thickness above the claypan was measured using procedures as outlined in Doolittle et al. (1994) and ranged from <10 cm to >100 cm. The mean annual temperature is 12°C, and the mean annual precipitation is 1004 mm (USDA-NRCS, 1995).

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[1] Mention of trade name 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 or the University of Missouri.

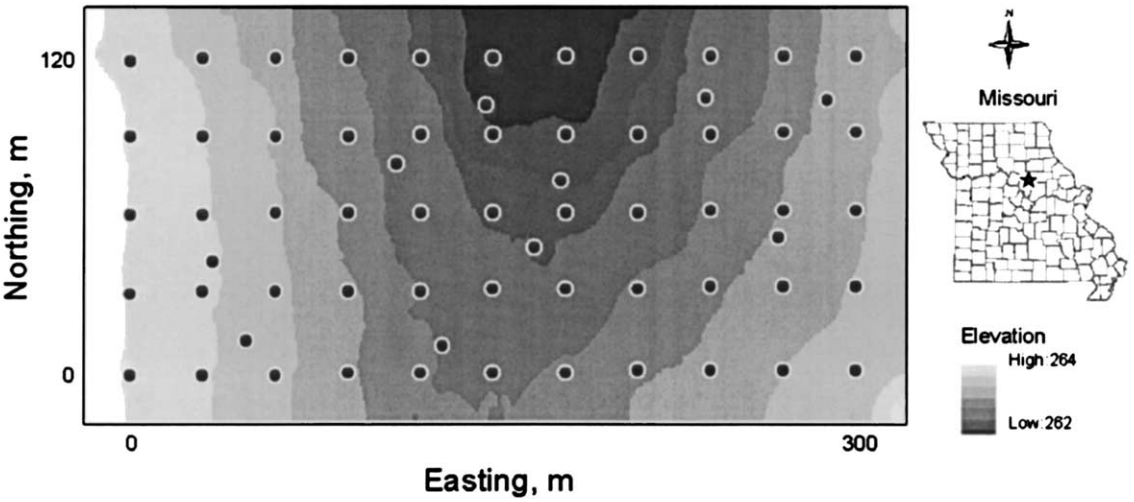

Fig. 2. Research site and soil sampling design.

This site has been managed in a corn–soybean crop rotation under mulch tillage since 1991 (Kitchen et al., 1997).

Measurements and Analysis

Soil samples were collected in June 2002 from between recently planted soybean rows. Samples were taken at 0- to 7.5-, 7.5- to 15-, and 15- to 30-cm soil depths on an evenly spaced 30-m grid within the 4-ha subfield area (Fig. 2). These sample depths were chosen because we were most interested in soil properties associated with the concept of soil quality, and these depths coincide with many previous similar investigations (Wander and Bollero, 1999; Brejda et al., 2000; Kettler et al., 2000; and Johnson et al., 2001). An additional 10 samples were taken at random locations, giving a total of 65 sample sites. Three 5.5-cm-diam. cores were taken and combined at each sampling site. Approximately 115 cm^3 of soil from each sample was dried in the oven at 105°C for 3 d. Approximately 170 cm^3 of each sample was refrigerated at 4°C. The remainder of the sample was air dried and ground to pass a sieve with 2-mm openings.

Soil physical properties measured included soil particle size distribution (pipette method) as outlined by the National Soil Survey Center Staff (1996). The D_b was calculated using oven-dried mass of the sample divided by the sample volume (Blake and Hartge, 1986). Chemical properties consisted of CEC (1 *M* ammonium acetate extractable at pH 7.0), total organic C (dry combustion), total N (dry combustion), and P by the Bray 1 extraction method (Olsen and Sommers, 1982). Microbiological properties studied included soil enzyme analysis by the dehydrogenase method (Casida et al., 1964) and respired CO_2 using a 3-wk soil fumigation–incubation method (Johnson et al., 1994). At every second sampling site, infiltration rates were measured using 25-cm-diam. single-ring infiltrometers (Bouwer, 1986). The ring was driven 15 cm into the soil and a positive head of 50 mm was maintained inside the ring using the Mariotte system during the infiltration test. A modified Green and Ampt equation model was used to estimate saturated hydraulic conductivity (Philip, 1957).

Electrical conductivity (in mS m^{-1}) was obtained using the EM38 (Geonics Limited, 1998) at each soil sample location. Readings were obtained at 0, 15, 20, and 30 cm above the ground. For aboveground measurement, the EM38 was placed on a cardboard box (depth 15 cm × width 20 cm × height 30 cm). A real-time kinematic GPS survey with a vertical and horizontal accuracy of 2- to 3- and 3- to 5-cm resolution, respectively, was used to calculate elevation and slope from DEM, and to identify sampling locations.

A combine equipped with a commercial yield-sensing, GPS-based (accuracy 1–2 m) recording system was used to map soybean and corn yield of the field from 1993 to 2002. Yield data were cleaned for removing error and kriged for interpolating 10-m grid data set as described in Kitchen et al. (2003). Yield data from an interpolated data set were selected at the same locations used for soil sampling and EC_a measurements. These multiyear yield data were used to identify relationships to the EC_a and claypan soil properties. Available yield data included 4 yr of corn and 5 yr of soybean. Grain sorghum grown in 1995 was omitted for this analysis.

With the exceptions of microbial properties and surface soil P (because of P fertilization), we concluded that the measured set of soil and landscape properties would be relatively static seasonally, and over years, and could be related to the decade-long yield data set.

Statistical Data Analysis

Means, minimums, maximums, medians, SDs, and CVs were calculated. Data normality was tested by skewness and kurtosis. Pearson correlation coefficients were calculated for all pairs of soil property, EC_a, and crop yield data. Regression models were derived to predict soil properties and crop yield using EC_a. Transformed, linear, and quadratic models of EC_a were evaluated to find the best-fitting models to predict soil properties. For validation of soil property regression models derived from soil EC_a, 20 additional samples were obtained from the same field during the summer of 2002, analyzed in the laboratory using the same procedures, and compared with the regression results.

RESULTS AND DISCUSSION

Soil and Landscape Properties

Soil properties at the deepest sampling depth (15–30 cm) were generally more normally distributed than at the shallower depths (Table 1). Similarly, most soil property values at the deepest depth were noticeably different from the shallower sampling depths. For example, mean values of clay content and CEC at the 15- to 30-cm sampling depth were higher than at shallower

Table 1. Descriptive statistics of soil and landscape properties.

Properties	*n*	Depth†	Mean	Min.	Max.	Median	SD	CV	Skw.‡	Krt.§
			Static soil properties							
Elevation, m	65		263	262	264	263	0.4	0.2	0.1	−0.8
Slope, %	65		0.5	0.1	0.9	0.4	0.1	26	0.6	2.6
Ksat¶, mm h^{-1}	29		1.9	0.1	7.5	1.6	1.5	76	1.7	4.0
Bulk density, Mg m^{-3}	65	1	1.3c#	1.1	1.7	1.3	0.1	9	0.6	1.2
		2	1.6a	1.3	1.7	1.6	0.1	5	−1.0	2.1
		3	1.5b	1.3	1.7	1.5	0.1	8	−0.3	−1.1
Clay, %	65	1	17c	14	23	16	2.0	12	1.1	1.0
		2	20b	14	56	18	7.4	36	2.9	9.7
		3	41a	13	63	45	15.8	38	−0.3	−1.4
Silt, %	65	1	76a	67	82	76	3.7	5	−0.2	−0.8
		2	73a	43	83	73	7.4	10	−1.7	4.1
		3	55b	33	81	51	14.4	26	0.4	−1.2
Fine silt, %	65	1	40a	32	52	38	4.9	12	1.0	0.2
		2	41a	24	54	41	5.4	13	0.1	1.1
		3	33b	21	51	31	8.4	26	0.5	−1.0
Coarse silt, %	65	1	36a	25	42	36	3.4	9	−0.8	0.6
		2	32b	19	38	32	4.1	13	−0.9	1.1
		3	23c	10	54	21	7.4	33	1.5	3.8
Sand, %	65	1	7.6a	1.9	13.3	7.6	2.9	39	−0.1	−0.9
		2	6.9a	1.4	12.5	7.1	2.8	40	0.1	−0.6
		3	3.7b	0.6	11.1	3.6	2.3	61	0.7	0.4
CEC, cmol kg^{-1}	65	1	14.1b	12.0	16.8	14.0	1.1	8	0.3	−0.5
		2	14.9b	11.3	33.8	13.6	3.9	26	3.0	10.5
		3	25.9a	11.7	40.6	27.7	9.0	35	−0.2	−1.5
Total organic C, %	65	1	1.23a	0.9	1.6	1.2	0.2	13	0.2	−0.1
		2	0.80c	0.6	1.0	0.8	0.1	12	0.1	−0.1
		3	0.89b	0.5	1.3	0.9	0.2	17	0.0	0.4
Total N, %	65	1	0.11a	0.08	0.14	0.11	0.01	14	−0.2	−0.5
		2	0.08c	0.03	0.1	0.08	0.01	15	−0.8	2.1
		3	0.09b	0.05	0.12	0.09	0.02	20	−0.3	−0.3
			Dynamic soil properties							
Bray-1 P, mg kg^{-1}	65	1	13.6a	5.8	77.4	12.1	9.3	69	5.2	34.6
		2	4.2b	0.8	17.9	3.9	2.2	52	3.9	23.8
		3	1.9c	0.3	5.4	1.4	1.3	72	0.9	−0.3
Soil enzyme, µg TPF (dry g soil)$^{-1}$ d^{-1}	65	1	135	50	273	124	49.6	37	0.8	0.6
Microbial biomass C, CO_2 mg kg^{-1} d^{-1}	61	1	86	52	125	84	18.1	21	0.4	−0.6

† 1, 0- to 7.5-cm sampling depth; 2, 7.5- to 15-cm sampling depth; 3, 15- to 30-cm sampling depth.

‡ Skw., skewness.

§ Krt., kurtosis.

¶ Ksat, saturated hydraulic conductivity.

\# Comparing across soil depth, values of a given soil and landscape property with the same letter are not significantly different ($P < 0.05$) using Duncan's multiple range test.

depths. Clay content at the deepest depth was more than twice that of the shallower sampling depths. The proportion of the total organic C, total N, and the Bray-1 P were clearly higher at the 0- to 7.5-cm depth than the deeper sampling depths.

Differences between the shallow sampling depth and the deepest sampling depth can be attributed to three factors. First, during the 10 yr before sampling, tillage operations were primarily disc and field cultivation to a depth of 10 to 15 cm. Therefore, organic matter from plant residue incorporation as well as fertilizer amendments (e.g., P) was mostly stratified within the surface 15 cm of soil. Second, over much of the sampled area, the upper boundary of the B_t horizon was between 15 cm and 30 cm. Therefore, the deepest sampling depth often included a portion of the B_t horizon, which has soil characteristics markedly different than topsoil. Third, the 15- to 30-cm sampling depth was twice the thickness of the other two. Consequently, this deepest sample depth had a greater chance of encompassing multiple horizons compared with the shallower sample depths. These latter two points are supported by the generally higher CV of most soil properties at the 15- to 30-cm depth samples compared with the shallower depths (Table 1).

Elevation and slope data show that the research area was relatively flat. Elevation ranged from 262 to 264 m and slope calculated from elevation was <1% across the field. Microbial properties, soil enzymes and microbial biomass C, were quite variable among samples (CVs of 37 and 21%, respectively). The fluctuation in soil microbial measurements, which we attribute to uneven mixing of crop residues with tillage, is similar to what others have found (Wander and Bollero, 1999). The mean value of saturated hydraulic conductivity was 1.9 mm h^{-1} and also varied greatly within the field. Two characteristics could be used to explain this wide variation. The first characteristic is the depth to the claypan, which was very different across the experimental area. Since the claypan horizon is a major controlling feature for hydrologic processes in these soils, variation in its depth will likely greatly alter saturated hydraulic conductivity. The second characteristic is that claypan soils crack deep into the subsoil under dry conditions, creating preferential flow pathways. These pathways either swell shut with rewetting or fill in with topsoil that has less clay. The spacing of soil cracks was not measured in this research but has been observed to be generally >30 cm (Baer et al., 1993). Thus, infiltration data would have varied depending on where past cracking was relative to placement of the 25-cm-diam. infiltrometer.

Table 2. Descriptive statistics of apparent soil electrical conductivity measurements (25 June 2002).

Sensor height	*n*	EM38 horizontal mode								EM38 vertical mode							
		Mean	Min.	Max.	Med.	SD	CV	Skw.†	Krt.‡	Mean	Min.	Max.	Med.	SD	CV	Skw.	Krt.
cm		$\mathrm{mS\ m^{-1}}$					%			$\mathrm{mS\ m^{-1}}$					%		
0	65	47	30	65	47	6.9	15	−0.1	0.0	60	38	83	60	8.2	14	−0.2	0.9
15	65	37	22	49	36	5.4	15	−0.3	0.0	53	35	73	53	7.1	14	−0.1	0.7
20	65	34	21	44	34	4.8	14	−0.3	−0.2	50	34	71	51	6.8	13	0.0	0.9
30	65	30	18	39	30	4.3	14	−0.4	−0.3	46	28	57	47	6.3	14	−0.6	0.4

† Skw., skewness.
‡ Krt., kurtosis.

Apparent Soil Electrical Conductivity

The EC_a was normally distributed for sensor heights and sensing modes (Table 2). Vertical dipole mode EC_a produced higher values compared with horizontal dipole mode EC_a for all sensor heights. In general, the trend was for EC_a readings to decrease as the sensor was lifted above the ground, which was expected since air is much less conductive than soil (McNeill, 1992). The EC_a at greater heights above the ground had slightly lower SDs for both reading modes.

Corn and Soybean Yield

Corn and soybean yield variability were high during the nine crop years. Generally, crop yields were below the long-term average due to droughty growing conditions in 1994, 1999, and 2002 (Table 3). The year of the lowest yield for corn (1999) and soybean (1994) had the largest CV for each crop. Conversely, the year of the highest yield for soybean (1996) had the smallest variation. Thus, within-field yield variability increased with lack of growing-season precipitation (Fig. 3). Previous studies have shown that in below-average precipitation years, topsoil thickness is a dominant feature affecting plant water supply and yield (Kitchen et al., 1999).

Soil Properties Correlated and Regressed to EC_a

Statistically significant ($P < 0.01$) correlations between EC_a with the sensor at the soil surface (in both horizontal and vertical dipole mode) and soil/landscape properties were compared and correlations were generally found to be higher than for the same properties with the sensor raised above the ground (Table 4). The EC_a was significantly positively correlated with clay content with correlation values greatest at the 15- to 30-cm depth. In contrast, EC_a was negatively correlated with silt content. Sand content in this soil was minor relative to silt and clay content (Table 1), and as such, correlations with EC_a were generally low or nonsignificant, particularly with increasing depth of sampling. These results were similar to previous findings (Mueller et al., 2003).

Soil particle distribution in the soil profile can be an important factor contributing to EC_a (Sudduth et al., 2003, 2005). Physical contact between soil particles allows for higher electrical conductivity and is known to be greater with clay than with sand- or silt-sized particles (Rhoades et al., 1976; Corwin and Lesch, 2003). The CEC for claypan soil is mostly generated from clay-sized particles. Therefore, it is not surprising that correlations for CEC were very similar to those for clay.

Bulk density was generally not well correlated to EC_a in the top two sampling depths, but D_b at the 15- to 30-cm sampling depth was negatively correlated with EC_a (Table 4). We attribute improved correlation in the deeper depth to the fact that the claypan horizon was often included in this sampling depth. Pore space increases with clay content, thus decreasing the bulk density. So, D_b is related to total clay content in the 15- to 30-cm sampling depth. The fact that tillage affects the top two layers, but does not greatly affect the third, likely also contributed to this result. P was not correlated with EC_a at the two shallowest sampling depths. Again, we attribute this to fertilization and soil disturbance, with tillage influencing the shallow sampling depths. Significant negative correlation existed between EC_a

Table 3. Descriptive statistics of crop yield data (n = 65) and precipitation.

Crop	Year	Crop yield								Precipitation	
		Mean	Min.	Max.	Median	SD	CV	Skw.†	Krt.‡	Total growing season§	July to August
		$\mathrm{kg\ ha^{-1}}$					%			cm	
Corn	1993	7120	5530	8200	7180	540	8	−0.4	0.4	102.7	29.4
	1997	6370	4200	9000	6500	1270	20	−0.0	−1.1	49.4	13.1
	1999	2320	1380	3980	2190	560	24	0.8	0.4	47.5	4.3
	2001	5900	4700	7290	5860	620	11	0.2	−0.6	61.4	11.0
	Avg.	5428	3953	7118	8433	748				65.3	14.5
Soybean	1994	1480	1030	2450	1450	290	20	1.0	1.1	48.8	4.9
	1996	3050	2740	3180	3080	110	4	−1.2	0.9	60.2	19.2
	1998	2010	1540	2240	2040	150	7	−1.1	1.3	73.1	19.1
	2000	2520	1920	2870	2530	200	8	−0.6	0.5	62.0	29.4
	2002	1960	1530	2370	1960	160	8	−0.2	0.3	58.0	14.0
	Avg.	2204	1752	2622	2212	182				60.4	17.3

† Skw., skewness.
‡ Krt., kurtosis.
§ Precipitation from April through September.

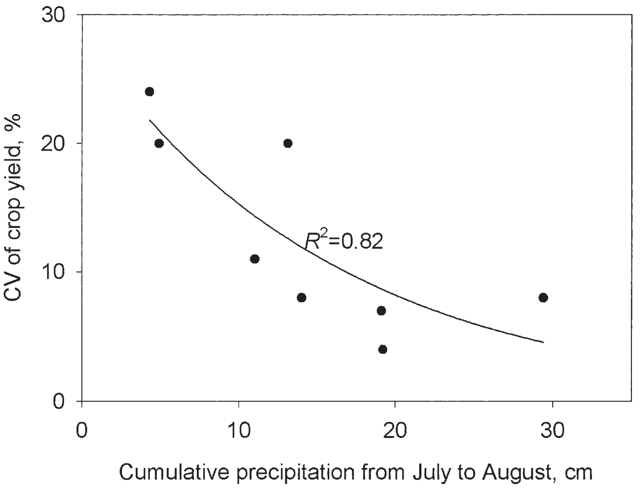

Fig. 3. Relationship between crop yield variation and cumulative precipitation from July to August.

and Bray-1 P at the deepest sampling depth (15–30 cm). A decrease in Bray-1 P with an increase in EC_a may be explained by P adsorption as clay content increases (Johnson et al., 2001; Heiniger et al., 2003).

Total organic C, total N, saturated hydraulic conductivity, and soil microbial properties were not correlated with EC_a (Table 4). Elevation was positively correlated with EC_a readings. Slope was also positively correlated, but with lower correlation values and mostly with vertical EC_a readings. Sedimentation from water erosion into foot-slope areas within the landscape (i.e., lowest elevation) buried the claypan, resulting in lower EC_a values. Conversely, the claypan was nearer the surface for eroded shoulder and side-slope positions, giving higher EC_a values. This relationship of EC_a to landscape properties was similar to that reported in a previous study on claypan soils (Kitchen et al., 2003).

Soil properties at each sampling depth were regressed against EC_a (0-cm height). Coefficients of determination for linear and quadratic regression model between EC_a and soil properties were plotted (Fig. 4). This figure not only shows which soil properties were best predicted by EC_a, but also how the prediction improved between linear and quadratic models. At the shallow sampling depth, predictions of many soil properties were improved using a quadratic model of EC_a instead of the simple linear regression. For example, prediction of soil

Table 4. Correlation coefficients among soil and landscape properties and apparent soil electrical conductivity (EC_a), by sensor height.†

			EM38 Horizontal mode				EM38 Vertical mode			
Properties	***n***	**Depth‡**	$EC_{a\text{-}0}$	$EC_{a\text{-}15}$	$EC_{a\text{-}20}$	$EC_{a\text{-}30}$	$EC_{a\text{-}0}$	$EC_{a\text{-}15}$	$EC_{a\text{-}20}$	$EC_{a\text{-}30}$
				Static soil properties						
Elevation, m	65		0.53***	0.55***	0.52***	0.58***	0.62***	0.62***	0.62***	0.59***
Slope, %	65		0.37**	0.28**	0.25*	0.23	0.43***	0.39**	0.40**	0.39**
Ksat, mm h^{-1}§	29		−0.04	<0.01	−0.07	−0.10	0.02	0.03	0.03	−0.04
Bulk density, Mg m^{-3}	65	1	0.33**	0.35**	0.29**	0.35**	0.27*	0.28*	0.28*	0.30*
		2	<0.01	0.02	0.04	<0.01	−0.02	−0.03	−0.03	−0.01
		3	−0.56***	−0.54***	−0.53***	−0.49***	−0.51***	−0.50***	−0.52***	−0.49***
Clay, %	65	1	0.25*	0.21	0.22	0.20	0.10	0.13	0.12	0.15
		2	0.49***	0.44***	0.44***	0.40**	0.34**	0.36**	0.36**	0.37**
		3	0.77***	0.75***	0.73***	0.71***	0.74***	0.71***	0.71***	0.72***
Silt, %	65	1	−0.55***	−0.52***	−0.50***	−0.47***	−0.48***	−0.49***	−0.47***	−0.48***
		2	−0.61***	−0.56***	−0.55***	−0.51***	−0.49***	−0.48***	−0.48***	−0.51***
		3	−0.78***	−0.76***	−0.74***	−0.73***	−0.76***	−0.72***	−0.72***	−0.74***
Fine silt, %	65	1	−0.67***	−0.67***	−0.66***	−0.64***	−0.66***	−0.63***	−0.63***	−0.65***
		2	−0.68***	−0.67***	−0.65***	−0.63***	−0.59***	−0.58***	−0.57***	−0.59***
		3	−0.75***	−0.74***	−0.74***	−0.72***	−0.70***	−0.67***	−0.67***	−0.70***
Coarse silt, %	65	1	0.37**	0.40***	0.40**	0.40***	0.43***	0.38**	0.39**	0.40***
		2	−0.21	−0.13	−0.14	−0.09	−0.10	−0.11	−0.11	−0.14
		3	−0.68***	−0.65***	−0.62***	−0.60***	−0.69***	−0.66***	−0.65***	−0.66***
Sand, %	65	1	0.52***	0.52***	0.49***	0.47***	0.55***	0.54***	0.52***	0.52***
		2	0.32*	0.31*	0.29*	0.29*	0.37**	0.32**	0.31*	0.36**
		3	−0.39**	−0.37**	−0.36**	−0.31*	−0.32*	−0.32*	−0.32**	−0.27*
CEC, cmol kg^{-1}	65	1	0.39**	0.35**	0.31*	0.30*	0.26*	0.30*	0.28*	0.21
		2	0.52***	0.47***	0.46***	0.42***	0.38**	0.39**	0.39**	0.38**
		3	0.80***	0.77***	0.74***	0.71***	0.78***	0.74***	0.75***	0.75***
Total organic C, %	65	1	−0.18	−0.17	−0.20	−0.17	−0.12	−0.10	−0.10	−0.21
		2	0.11	0.10	0.07	0.10	0.04	0.10	0.08	0.01
		3	0.22	0.19	0.16	0.19	0.20	0.17	0.18	0.20
Total N, %	65	1	−0.19	−0.19	−0.21	−0.21	−0.14	−0.12	−0.13	−0.2
		2	−0.02	−0.05	−0.07	−0.06	−0.06	−0.02	−0.02	−0.09
		3	0.26*	0.22	0.16	0.20	0.22	0.16	0.17	0.17
				Dynamic soil properties						
Bray-1 P, mg kg^{-1}	65	1	0.02	0.01	0.01	−0.01	0.05	0.08	0.07	−0.02
		2	0.04	0.05	0.06	0.06	0.06	0.11	0.09	0.03
		3	−0.63***	−0.63***	−0.59***	−0.59***	−0.66***	−0.62***	−0.63***	−0.66***
Soil enzyme, μg TPF (dry g soil)$^{-1}$ d^{-1}	65	1	0.04	0.03	0.03	0.08	0.17	0.19	0.18	0.19
Microbial biomass C, CO_2 mg kg^{-1} d^{-1}	61	1	0.05	0.04	0.07	0.05	0.11	0.11	0.10	0.11

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† $EC_{a\text{-}0}$, 0-cm height; $EC_{a\text{-}15}$, 15-cm height; $EC_{a\text{-}20}$, 20-cm height; $EC_{a\text{-}30}$, 30-cm height above ground.
‡ 1, 0- to 7.5-cm sampling depth; 2, 7.5- to 15-cm sampling depth; 3, 15- to 30-cm sampling depth.
§ Ksat, saturated hydraulic conductivity.

test P in the surface sample was greatly improved by using the quadratic model (coefficient of determination improved from 0.2 to 0.4). In general, physical soil properties were better estimated from the EC_a quadratic model. Using a similar approach, other transformations of EC_a were considered, including inverse, log, and exponential models. Regressions using these transformed terms (data not included) almost always gave a coefficient of determination less than models using a quadratic term. Also, the ratio of EC_a vertical to EC_a horizontal and the difference between EC_a vertical and EC_a horizontal were tested as variables for predicting soil properties. Previous studies have shown the ratio of shallow EC_a to deep EC_a to be helpful in expressing the leaching fraction of a soil profile (Corwin et al., 1999). However, neither the ratio or difference variables improved regression coefficients of determination (data not shown) over those obtained with the linear or quadratic models.

For validation of soil property models derived from soil EC_a, validation of selected regression models (Table 5) were compared with measurements taken from 20 additional sample locations from the same field. Models selected were significant ($P < 0.05$) and generally were those parameters with the highest coefficients of determination. In this validation dataset, the average of measured soil properties was very similar to the average obtained from the models (i.e., predicted). Quality of the prediction, as indicated by the SE between observed and predicted sol properties, are shown for these selected models. In all cases, the SE was less than the SD of measured soil properties. We conclude that the models derived from soil EC_a could provide reasonable estimates of these soil properties.

Soil Properties Correlated to Crop Grain Yield

Statistically significant correlation coefficients of soil properties to crop grain yield are provided in Table 6.

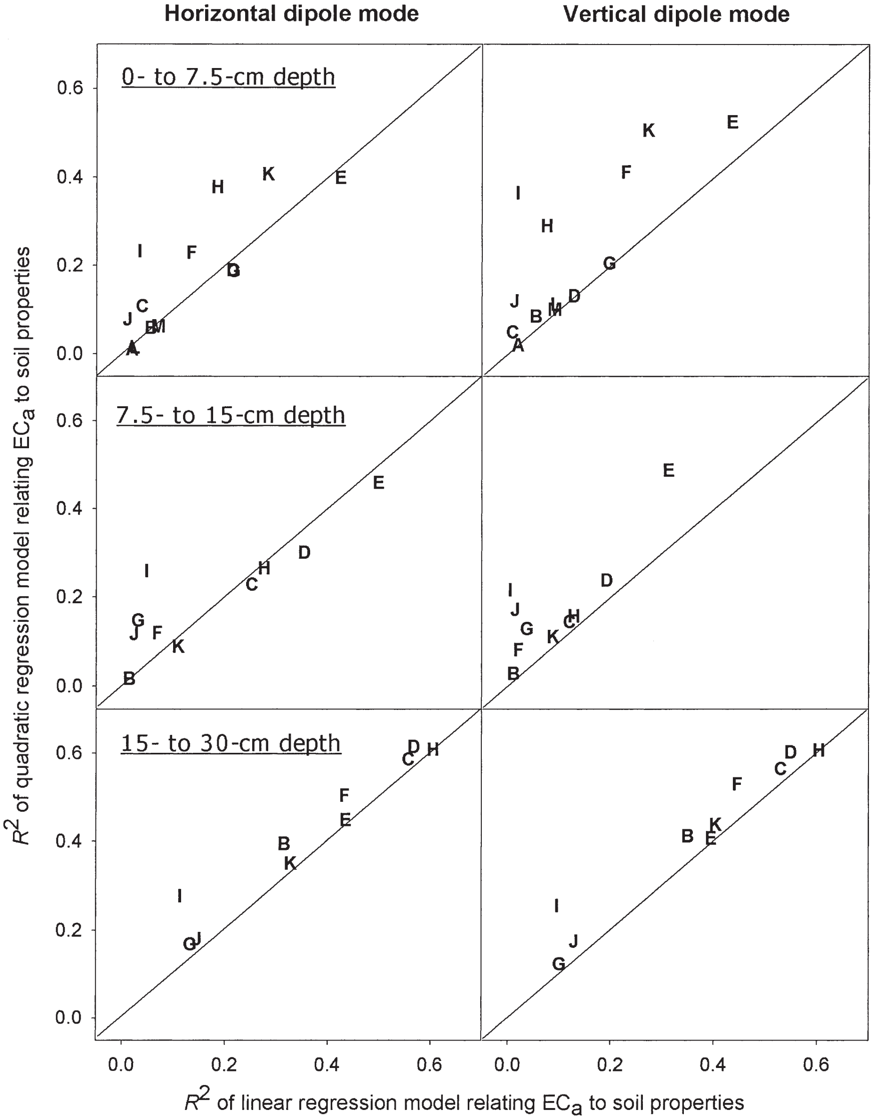

Fig. 4. Comparison of linear regression model and quadratic regression model of apparent soil electrical conductivity (EC_a) to soil quality indicators by soil sampling depths. A, saturated hydraulic conductivity; B, bulk density; C, clay; D, silt; E, fine silt; F, coarse silt; G, sand; H, cation exchange capacity; I, total organic carbon; J, total N; K, phosphorus; L, soil enzyme; M, microbial biomass (CO_2).

Table 5. Selected regression models using apparent soil electrical conductivity (EC_a)† to predict soil properties were validated with an independent soil sample data set ($n = 20$).

Soil depth	Soil property	Selected model	R^2 or r^2	*P* value of *F* test	Validation		
					Measured	Predicted	SE
cm							
0–7.5	total organic C, %	$3.84 - 0.09EC_a + 0.0007EC_a^2$	0.26	0.02	1.33	1.26	0.15
	Bray1-P, mg kg^{-1}	$106.6 - 3.3EC_a + 0.03EC_a^2$	0.44	<0.001	19.6	15.7	5.3
15–30	bulk density, Mg m^{-3}	$1.9 - 0.007EC_a$	0.35	<0.001	1.53	1.50	0.07
	clay, %	$-43.6 + 1.42EC_a$	0.53	<0.001	35.3	38.9	15.6
	CEC, cmol kg^{-1}	$12 + 0.036EC_a$	0.60	<0.001	27.8	24.7	9.0
	Bray1-P, mg kg^{-1}	$8.2 - 0.11EC_a$	0.40	<0.001	2.03	2.0	1.1

† Vertical dipole mode with 0-cm height EC_a was obtained to predict model.

Soil bulk density; proportion of clay, silt, and coarse silt; CEC; and Bray-1 P were generally more highly correlated with yield at the 15- to 30-cm depth than at the other depths. Fine silt and sand at the 0- to 7.5-cm depth were also highly correlated with yield. Organic C, total N, saturated hydraulic conductivity, and microbial properties showed little correlation to yield.

Significant correlations generally fell into two distinguishable groups when examined by crop year. Within a soil property and sampling depth, the sign of the correlation (i.e., positive or negative) identifies the grouping. These two groups correspond to the amount of July through August precipitation received, with one group having <15-cm rainfall (1994, 1997, 1999, and 2001) and the other group having >15-cm rainfall during those two months (1996, 1998, and 2000) (Tables 3 and 6). While this is a limited set of climate data and ignores other critical climate variables (e.g., temperature), we conclude from this grouping that when precipitation is approximately <15 cm in July and August, water deficiency will induce crop stress in these soils and reduce grain yield. Claypan soils have relatively low drought tolerance because the high-clay subsoil has poor infiltration and diminished profile plant-available water

Table 6. Correlation coefficients among soil and landscape properties measured in 2002 and crop yields by year.

Properties	*n*	Depth†	Corn				Soybean				
			1993	1997	1999	2001	1994	1996	1998	2000	2002
					Static soil properties						
Elevation, m	65		0.21	−0.71***	−0.69***	−0.68***	−0.52***	0.29*	0.45***	0.53***	−0.33**
Slope, %	65		−0.24	−0.52***	−0.49***	−0.35**	−0.33**	0.17	0.32*	0.56***	−0.24
Ksat, mm h^{-1}‡	29		−0.29	−0.38	−0.32	−0.22	−0.19	−0.03	0.01	0.16	−0.16
Bulk density, Mg m^{-3}	65	1	0.15	−0.07	−0.17	−0.16	−0.26*	0.28**	0.34**	0.23	0.03
		2	0.10	0.11	−0.06	0.06	−0.13	0.04	−0.04	−0.11	0.15
		3	−0.17	0.51***	0.44***	0.60***	0.47***	−0.21	−0.32**	−0.22	0.21
Clay, %	65	1	0.24*	0.12	−0.01	0.15	−0.15	0.31*	−0.02	−0.07	0.27*
		2	0.14	−0.37**	−0.36**	−0.36**	−0.45***	0.34**	0.15	0.24	−0.10
		3	0.21	−0.71***	−0.75***	−0.73***	−0.74***	0.49***	0.57***	0.65***	−0.19
Silt, %	65	1	−0.19	0.43***	0.52***	0.27*	0.44***	−0.44***	−0.30*	−0.41***	−0.04
		2	−0.15	0.50***	0.54***	0.43***	0.57***	−0.45***	−0.32**	−0.43***	0.09
		3	−0.21	0.69***	0.76***	0.72***	0.75***	−0.51***	−0.61***	−0.68***	0.18
Fine silt, %	65	1	−0.09	0.70***	0.79***	0.61***	0.72***	−0.48***	−0.55***	−0.71***	0.21
		2	−0.09	0.57***	0.68***	0.51***	0.70***	−0.48***	−0.49***	−0.61***	0.16
		3	−0.29*	0.60***	0.68***	0.64***	0.67***	−0.53***	−0.55***	−0.56***	0.19
Coarse silt, %	65	1	−0.07	−0.55***	−0.58***	−0.58***	−0.55***	0.21	0.47***	0.57***	−0.35**
		2	−0.14	0.14	0.07	0.10	0.09	−0.18	0.06	0.03	−0.04
		3	−0.06	0.70***	0.74***	0.69***	0.73***	−0.42***	−0.56***	−0.69***	0.15
Sand, %	65	1	0.07	−0.62***	−0.65***	−0.45***	−0.46***	0.35**	0.39**	0.57***	−0.14
		2	0.01	−0.32**	−0.45***	−0.18	−0.29*	0.29**	0.44***	0.49***	0.01
		3	−0.10	0.50***	0.34**	0.49***	0.37**	−0.11	−0.13	−0.22	0.17
CEC, cmol kg^{-1}	65	1	0.29*	−0.03	−0.06	0.17	0.02	0.18	0.10	0.04	0.14
		2	0.14	−0.35**	−0.34**	−0.30*	−0.41***	0.31*	0.18	0.24	−0.10
		3	0.29*	−0.64***	−0.69***	−0.67***	−0.67***	0.45***	0.57***	0.56***	−0.17
Total organic C, %	65	1	0.05	0.20	0.27*	0.42***	0.51***	−0.26*	−0.19	−0.17	0.18
		2	0.05	0.16	0.18	0.39**	0.28*	−0.10	−0.12	−0.17	0.13
		3	0.18	0.03	0.06	0.13	−0.09	−0.10	−0.07	−0.13	0.07
Total N, %	65	1	−0.31*	0.23	0.22	0.45***	0.36**	−0.27*	−0.35**	−0.19	0.05
		2	−0.01	0.21	0.18	0.30*	0.30**	−0.04	−0.14	−0.21	0.04
		3	0.09	−0.05	−0.02	−0.01	−0.12	−0.04	0.09	−0.03	−0.02
					Dynamic soil properties						
Bray-1 P, mg kg^{-1}	65	1	0.02	0.08	0.13	0.11	0.27*	−0.35**	−0.04	−0.23	−0.04
		2	0.03	0.21	0.19	0.17	0.29*	−0.27**	0.14	−0.18	0.02
		3	−0.05	0.81***	0.81***	0.78***	0.72***	−0.41***	−0.50***	−0.70***	0.25*
Soil enzyme, μg TPF (dry g soil)$^{-1}$ d^{-1}	65	1	0.09	−0.16	−0.12	−0.05	0.03	0.11	0.12	0.15	0.02
Microbial biomass C, CO_2 mg kg^{-1} d^{-1}	61	1	−0.06	<0.01	−0.02	0.11	0.14	−0.06	0.11	0.17	0.12

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† 1, 0- to 7.5-cm sampling depth; 2, 7.5- to 15-cm sampling depth; 3, 15- to 30-cm sampling depth.
‡ Ksat, saturated hydraulic conductivity.

Table 7. Correlation coefficients between apparent soil electrical conductivity (measured in 2002) and crop grain yield.

Sensor mode	Sensor height	Corn				Soybean				
		1993	1997	1999	2001	1994	1996	1998	2000	2002
	cm									
Horizontal	0	0.33**	−0.58***	−0.65***	−0.52***	−0.60***	0.45***	0.61***	0.63***	−0.16
	15	0.34**	−0.59***	−0.68***	−0.56***	−0.63***	0.42***	0.57***	0.62***	−0.18
	20	0.35**	−0.56***	−0.65***	−0.56***	−0.61***	0.46***	0.54***	0.60***	−0.17
	30	0.38**	−0.54***	−0.64***	−0.53***	−0.61***	0.45***	0.54***	0.60***	−0.18
Vertical	0	0.26*	−0.64***	−0.73***	−0.56***	−0.61***	0.36**	0.57***	0.63***	−0.23
	15	0.26*	−0.62***	−0.71***	−0.55***	−0.58***	0.38**	0.57***	0.62***	−0.20
	20	0.28*	−0.62***	−0.71***	−0.55***	−0.57***	0.36**	0.55***	0.61***	−0.22
	30	0.25*	−0.63***	−0.74***	−0.58***	−0.64***	0.37**	0.54***	0.62***	−0.26*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.

content (USDA-NRCS, 1995). The correlations from this dataset provide evidence of a *drought boundary* of about 15 cm for the July-through-August cumulative precipitation. When <15 cm of precipitation occurs, water deficiency stress will likely occur. When >15 cm of precipitation is received, deficiency stress will be minimal. This information may prove helpful in some management considerations (e.g., irrigation, grain yield estimation).

$\mathrm{EC_a}$ Correlated to Crop Yield

The $\mathrm{EC_a}$ was negatively correlated to corn and soybean yield in years with <15 cm of cumulative precipitation in July and August (1994, 1997, 1999, 2001, and 2002) (Table 7). In contrast, $\mathrm{EC_a}$ was positively correlated to corn and soybean yield for years with >15 cm of accumulative precipitation in July and August (1993, 1996, 1998, and 2000). Thus, the sign of the correlation between $\mathrm{EC_a}$ and yield followed the same pattern as correlations between soil properties and yield. While correlation analysis itself is far from a definitive analysis, we suspect this similar pattern in correlations is not coincidental. These results support the idea that $\mathrm{EC_a}$ may be used as a alternative measure for soil properties influencing crop production. As an example, these findings suggest that $\mathrm{EC_a}$ might be used to approximate subsoil P, which is usually ignored with a conventional soil sampling strategy (i.e., 0- to 15-cm sampling depth) for nutrient recommendations.

CONCLUSIONS

We found the best procedure of measuring $\mathrm{EC_a}$ using EM38 was operating it close to the soil surface and in horizontal dipole mode. This procedure provided the best relationship between $\mathrm{EC_a}$ and soil properties with the top 30 cm on a claypan field.

The $\mathrm{EC_a}$ can provide important information for characterizing claypan soil properties often associated with soil quality. In this study, we compared soil physical, chemical, and biological properties (measured in 2002) to $\mathrm{EC_a}$ and to crop yield across multiple years for a claypan soil field. We found that $\mathrm{EC_a}$ was significantly correlated to some soil properties (D_b, clay, silt, sand content, CEC, elevation, and slope). When using $\mathrm{EC_a}$ to predict soil properties, most regressions were significantly improved using a quadratic term in $\mathrm{EC_a}$, especially at the shallow sampling depth. Approximately 60% of the variation in silt, clay, and CEC for the 15- to 30-cm depth could be predicted using $\mathrm{EC_a}$. Selected regression models (i.e., D_b, clay, Bray1-P, CEC, and organic C) were validated with an independent soil sample data set ($n = 20$). Soil properties were similar between measured and predicted soil properties.

Some of the soil properties that were correlated to $\mathrm{EC_a}$ also helped characterize soil quality for crop production. The D_b, clay, silt content, CEC, and Bray1-P at the deepest sampling depth (15 to 30 cm) were highly correlated with crop yield. Crop yield variation was very high and showed a pattern (significantly correlated with July–August precipitation) over the 9 yr evaluated. The $\mathrm{EC_a}$ and soil properties were correlated with yield differently, depending on whether the July and August precipitation was greater or less than 15 cm. For these claypan soils, the type of relationship a soil property may have with yield is highly dependent on seasonal precipitation. Rainfall affected yield more than variations in soil properties. From our results, we propose a drought boundary of 15 cm of July and August precipitation and suggest it is a measure that could be used to help manage these soils.

This research showed that while claypan soil properties varied greatly by depth, and crop yield varied greatly by year, $\mathrm{EC_a}$ was significantly correlated with soil properties, especially some physical properties that impact crop yield. We conclude that soil $\mathrm{EC_a}$ has the potential to serve as a soil quality indicator for claypan soil productivity.

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