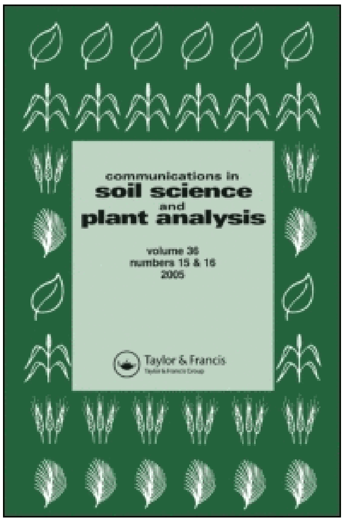

Communications in Soil Science and Plant Analysis
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597241

World's Oldest Cotton Experiment: Relationships between Soil Chemical and Physical Properties and Apparent Electrical Conductivity

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Online Publication Date: 01 June 2006

To cite this Article Siri-Prieto, G., Reeves, D. W., Shaw, J. N. and Mitchell, C. C.(2006)'World's Oldest Cotton Experiment: Relationships between Soil Chemical and Physical Properties and Apparent Electrical Conductivity',Communications in Soil Science and Plant Analysis,37:5,767 — 786

To link to this Article: DOI: 10.1080/00103620600564018

URL: http://dx.doi.org/10.1080/00103620600564018

Communications in Soil Science and Plant Analysis, 37: 767–786, 2006

ISSN 0010-3624 print/1532-2416 online
DOI: 10.1080/00103620600564018

World's Oldest Cotton Experiment: Relationships between Soil Chemical and Physical Properties and Apparent Electrical Conductivity

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Abstract: Measuring and mapping apparent soil electrical conductivity (EC_a) is a potentially useful tool for delineating soil variability. The "Old Rotation," the world's oldest continuous cotton (*Gossypium hirsutum* L.) experiment (ca. 1896), provides a valuable resource for evaluating soil spatial variability. The objectives of this study were to determine the relationship between soil chemical and physical properties and EC_a in the Old Rotation, to determine spatial differences in these properties, and to relate differences in these properties to long-term management effects. Soils at the site classified as fine, kaolinitic, thermic Typic Kanhapludults. Soil EC_a was measured at 0–30- and 0–90-cm depths ($EC_{a\text{-}30}$ and $EC_{a\text{-}90}$) using a Veris® 3100 direct contact sensor with georeferencing. Soils were grid sampled (288 points) at close intervals (1.5×3.0 m) for chemical properties and grid sampled (65 cells,

Received 30 April 2004, Accepted 1 August 2005
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7.5 × 6.9 m) for soil texture. Soil organic carbon (SOC) and total nitrogen (N), extractable phosphorus (P), potassium (K), calcium (Ca), pH, buffer pH, and estimated cation exchange capacity (CEC_{est}) were measured at two depths (0–5- and 5–15-cm). Soil EC_a was highly spatially correlated. The $EC_{a\text{-}30}$ was more highly correlated with clay content ($r = 0.58$, $P \leq 0.01$) and P($r = 0.43$, $P \leq 0.01$) than other soil properties. Total nitrogen and SOC had little or no relationship with $EC_{a\text{-}30}$. Cropping systems affected chemical properties in the Old Rotation, indicating crop rotation and cover crops are beneficial for soil productivity. The relatively poor relationship between soil chemical parameters and EC_a suggest that mapping plant nutrients and SOC using EC_a is problematic because of strong dependence on clay content.

Keywords: Clay content, crop rotation, long-term experiment, P, soil carbon, soil electrical conductivity, spatial variation

INTRODUCTION

Apparent electrical conductivity (EC_a) has recently been shown to be an effective and rapid indicator of soil variability and soil productivity (Kitchen, Sudduth, and Drummond 1999). Apparent soil electrical conductivity measures the capacity to conduct electrical current through the soil profile. Historically, soil EC_a has been used to evaluate salinity (Rhoades, Raats, and Prather 1976), but recently commercial devices have been developed that rapidly measure soil EC_a for use in management decisions.

Studies have shown that soil EC_a reflects texture variability (sand, silt, and clay content have a relatively low, medium, and high EC_a, respectively) (Williams and Hoey 1987). One of the most important factors influencing EC_a is the total volumetric water content of the soil (Rhoades et al. 1989), and this factor is strongly influenced by soil texture and bulk density. Other factors that influence soil EC_a include salinity, cation exchange capacity (CEC), and topsoil depth (Sudduth, Drummond, and Kitchen 2001). Therefore, EC_a has the potential to indirectly estimate variability of these properties providing the contributions of other soil properties affecting EC_a are known or can be estimated (Sudduth et. al. 1995).

Because EC_a integrates soil texture and moisture, two soil properties that greatly affect productivity, it can be used to assist in interpretation of spatial variation of crop productivity (Sudduth et al. 1995). Crop yield is extremely dependent on soil chemical and physical properties and the effectiveness of EC_a mapping for predicting productivity is dependent upon the degree to which these soil properties affect EC_a. Soil organic carbon is a major component for maintaining the quality of agricultural soil (Reeves 1997). However, with respect to determining SOC with EC_a, results have been conflicting and uncertain (Hartsock et al. 2000).

The Old Rotation (circa 1896), the world's oldest continuous cotton experiment, provides valuable and unique information for researching sustainable agricultural production (Siri-Prieto et al. 2002). The original and ongoing goal of this experiment is to evaluate best management practices for sustainable cotton production. It is a cotton rotation study that includes corn (*Zea Mays* L.), soybean [*Glycine max* (L.) Merr.], and small grains. Differences in amount and quality of crop residues returned to the soil and N fertilizer additions have been used to explain variable organic matter concentrations and nutrient availability among crop rotations (Mitchell and Entry 1998; Siri-Prieto et al. 2002). Winter legumes are included as a source of nitrogen in some treatments. All plots have received the same annual rate of P and K, and since 1997 all crops have been planted using conservation tillage with crop residues left as surface mulch (Mitchell, Reeves, and Delaney 2001). The Old Rotation provides an extensive database of soil fertility practices and cropping systems and occupies a 0.4-ha site with considerable soil variability due to Coastal Plain sediments overlying Piedmont soils. Thus, it offers a unique resource for evaluating the effects of soil spatial variability on management practices.

Mapping the Old Rotation using EC_a may help explain long-term variations in productivity in this experiment, as well as provide information on soil quality as a result of conservation tillage adoption. The objectives of this study were to determine the relationship between specific soil chemical and physical properties and EC_a in the Old Rotation, to determine spatial differences in these properties, and to relate differences in these properties to long-term management effects.

MATERIALS AND METHODS

Study Site

The Old Rotation experiment at Auburn University (85°W, 32°N), Alabama (ca. 1896), is the oldest continuous cotton experiment in the world (Mitchell and Entry 1998). Average annual precipitation at the site is approximately 1350 mm with a mean annual temperature of 18.3°C. A thin cap of unconsolidated Coastal Plain sediments overlies finer textured, highly weathered Piedmont soils. The soil is mostly Pacolet fine sandy loam (fine, kaolinitic, thermic Typic Kanhapludults) (Table 1).

Site Management

Like most experiments conducted at the beginning of the 20th century, treatments were not replicated in a standardized experiment design. There are 13 plots on 0.4 ha of land. Each plot is 42 m long by 6.5 m wide with 1 m alleys between plots (Figure 1). The treatments have undergone modifications since 1925 in terms of legumes used, fertilizer applications, and varieties. Cotton, corn, and soybean cultivars have been chosen based on Alabama Cooperative

Table 1. Characterization data for sampled pedon (fine, kaolinitic, thermic Typic Kanhapludult) in the Old Rotation experiment, Auburn, AL (ca. 1896) (Entry, Mitchell, and Backman 1996)

Horizon	Depth (cm)	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Ca ($cmol_c$ kg^{-1})	Mg ($cmol_c$ kg^{-1})	K ($cmol_c$ kg^{-1})	Na ($cmol_c$ kg^{-1})	ECEC[a] ($cmol_c$ kg^{-1})	CEC[b] ($cmol_c$ kg^{-1})	BS[c] (%)
Ap	0–25	667	203	130	0.8	0.3	0.2	<0.01	1.6	3.2	39.3
Bt1	25–41	324	201	475	1.6	1.3	0.1	<0.01	3.2	5.3	56.5
2Bt2	41–68	247	199	554	1.3	1.0	0.1	<0.01	2.7	9.6	25.2
2Bt3	68–96	188	196	616	0.7	0.5	0.1	<0.01	2.9	8.2	16.0
2Bt4	96–106	221	210	569	0.4	0.4	0.0	<0.01	2.3	7.1	11.6

[a]ECEC = effective cation exchange capacity.
[b]CEC = cation exchange capacity (ammonium acetate pH 7).
[c]BS = % base saturation.

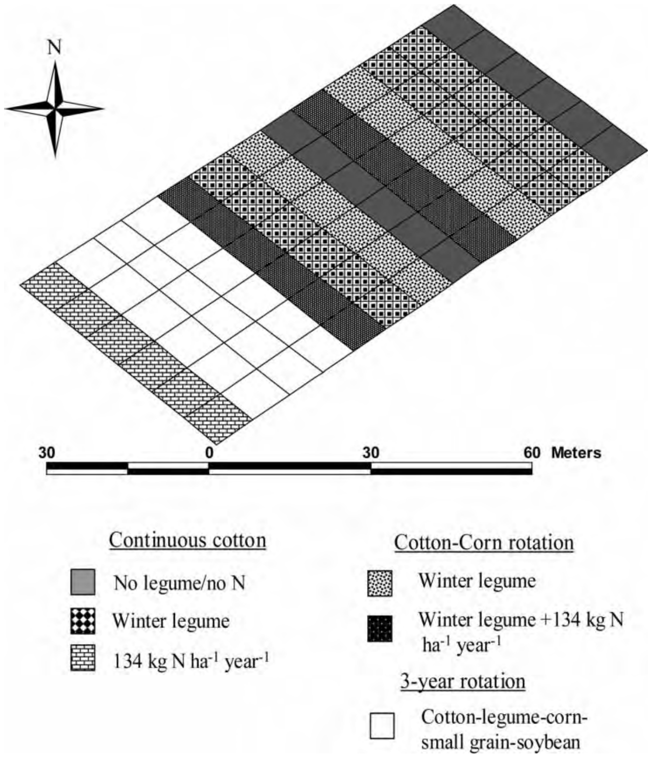

Figure 1. The Old Rotation experiment, Auburn, AL (ca. 1896) consists of 13 plots with six different cropping systems within three rotations.

Extension System (ACES) recommendations. Winter legumes that have been used include hairy vetch (*Vicia villosa* Roth), common vetch (*Vicia sativa* L.), and since 1956, crimson clover (*Trifolium incarnatum* L.).

Prior to the 1950s, oat (*Avena sativa* L.) was used in rotations requiring small grain; since then, cereal rye (*Secale cereale* L.) or wheat (*Triticum aestivum* L.) have been included as small-grain rotation crops. Cowpea (*Vigna unguiculata* L.) was grown as both a summer annual green manure crop and as a hay crop prior to 1956. Soybean as a cash crop replaced cowpea in 1956. Despite these changes, six basic cropping systems have been maintained within the 13 original plots (Figure 1, Table 2). All plots have received the same annual rate of P and K. However, the actual rate applied has gradually increased over the years from a total annual application of 11 and 18 kg ha^{-1} to 39 and 56 kg ha^{-1} since 1956, for P and K, respectively. Dolomitic limestone has been applied to each plot to maintain surface soil pH between 6.0 and 7.0 (Adams, Mitchell, and Bryant 1994).

Traditionally, all treatments were conventionally tilled using a moldboard plow and disk until 1990; chisel plowing and disking were used until 1996.

Table 2. Soil conditions for apparent electrical conductivity (EC_a) mapping in each plot used in the Old Rotation experiment, Auburn, AL

Cropping systems	Plot	Soil condition at EC_a mapped on December 1, 1999
Continuous cotton without legume[a]	1	Cotton residue
	6	
Continuous cotton + legume[a]	2	Cover crop[d]
	3	
	8	
Continuous cotton + N[b]	13	Cotton residue
2-yr cotton-corn + legume[a]	4	Corn residue, cover crop
	7	Cotton residue, cover crop
2-yr cotton-corn + legume[a] + N[b]	5	Corn residue, cover crop
	9	Cotton residue, cover crop
3-yr cotton-corn-small grain/ soybean + legume[a] + N[c]	10	Cotton residue, cover crop
	11	Corn residue, wheat[e]
	12	Soybean residue

[a]Legume = winter cover crop; crimson clover since 1956.
[b]Nitrogen applied to cotton or corn (134 kg ha^{-1} yr^{-1}).
[c]Nitrogen applied to small grain (67 kg ha^{-1} yr^{-1}).
[d]All cover crops were planted on Oct. 21, 1999.
[e]Wheat planted on Nov. 19, 1999.

In-row subsoiling to a depth of 40-cm has become a common practice since 1985 in all treatments. In spring of 1997, conservation tillage was implemented. This consists of planting into the killed cover crop or winter weed residue. In-row subsoiling has been applied without surface soil disruption with a Paratill® (Bigham Brothers, Inc., Lubbock, TX) bent-legged or KMC® (Kelley Manufacturing Co., Tifton, GA) narrow-shanked subsoiler each spring before planning corn, soybean, or cotton.

Sampling and Soil Analysis

In fall 1999, the Old Rotation was divided into GPS georeference points (1.5 × 3.0 m grid) for soil sampling. This resulted in 788 points within the 0.4-ha site. The samples that laid into alleys were not considered. Three samples were composited at each point. All points were sampled at two depths (0–5- and 5–15-cm). However, only 288 (average points/plot: 22.1) sampling points selected at random were analyzed. Samples were lightly crushed and sieved through a 2 mm mesh. Soil pH was determined on 1:1 soil/water suspension. Estimated cation exchange capacity (CEC_{est}) was calculated by summing the basic cations (Mg, Ca, K) and adding an estimate of exchangeable acidity based on buffer-pH (*B*pH) values (Adams, Mitchell, and

Bryant 1994). Phosphorus, K, Ca, and Mg were extracted using a Mehlich-1 (double acid) extraction (Adams, Mitchell, and Bryant 1994) and determined by inductively coupled argon plasma emission spectrometry (ICAP) (Soltanpour, Jones, and Worman 1982). Total soil organic carbon (SOC) and total nitrogen (N) were determined from finely ground soil (using a roller grinder) by dry combustion (Yeomans and Bremner 1991) using a nitrogen/carbon 1500 CNS analyzer (Fisons Instrument, Beverly, MA).

Samples for soil texture were taken in 2003. The Old Rotation was divided into geo-referenced 7.5 × 6.9 m grids resulting in 65 polygons. For practical reasons, the grid size for soil texture samples was upscaled from the random 288 samples within the 788-point generated grid every fourth or fifth point (dependent on grid point's proximity to alleys), as local scale variability for texture is much less than for chemical properties. An average of 4.4 sampling points for soil chemical properties resided within each soil texture polygon. Three samples were composited from within each polygon at the 0–15-cm depth. Forty-gram subsamples from a composite sample were taken. Particle size distribution was determined by sieving (2 mm) using the pipette method (Kilmer and Alexander 1949).

Apparent Soil Electrical Conductivity

Apparent soil electrical conductivity (EC_a) was measured on December 1, 1999 (soil conditions for EC_a sensing shown in Table 2), using a Veris® 3100 sensor (Veris Technologies, 2001). The sensor consists of six coulters, two of which introduce an electrical potential into the soil, the remaining four coulters are spaced to measure EC_a at two approximate depths, 0–30 cm ($EC_{a\text{-}30}$) and 0–90 cm ($EC_{a\text{-}90}$). The instrument was pulled with a tractor through the field at a constant speed ($2.0\,m\,s^{-1}$) in the northwest–southeast and in the northeast–southwest direction with approximately 3.70 m between passes (Figure 2). A total of 1418 EC measurement points were taken, providing an average 21.8 EC points by texture polygon. The instrument records EC_a at 1-s intervals. An average of 21.8 EC_a points resided within each soil texture polygon. Geographic position was simultaneously recorded using a Trimble AG132 DGPS System® (Trimble Navigation Ltd., Sunyvale, CA). For reporting purposes, EC_a was converted to mS m^{-1}. Measurements of EC_a between plots (alleys) were considered in the analysis.

Statistical Analysis

As a result of conventional tillage being practiced from 1896 to 1996, highly positive correlations were observed between the 0–5- and 5–15-cm depths for all individual soil chemical properties. Thus, comparisons between EC_a and

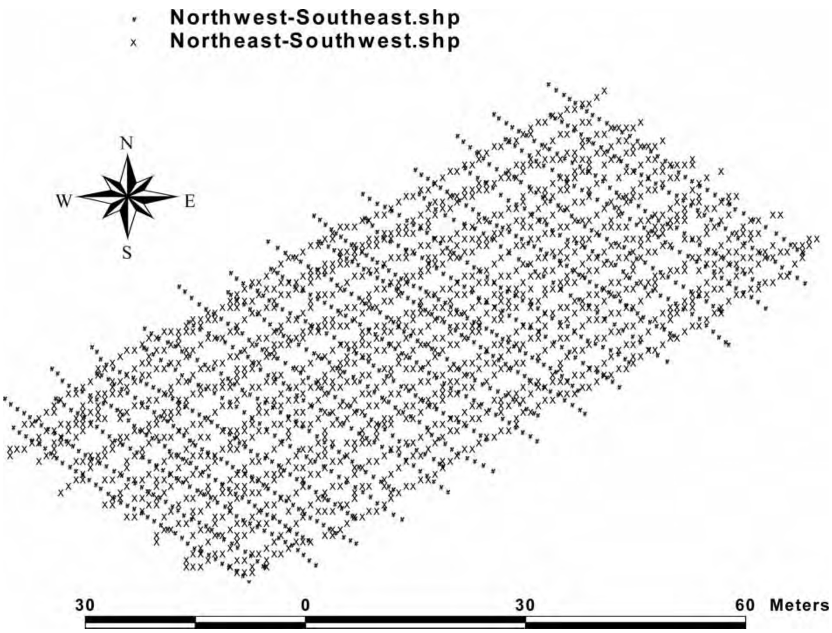

Figure 2. Map of data locations point for EC_a recorded every 1 s in the northwest–southeast and in the northeast–southwest direction with approximately 3.70 m between passes in the Old Rotation experiment, Auburn, AL (n = 2039).

soil properties were determined from samples averaged between 0–5- and 0–15-cm depths. The EC_a measurements and soil chemical property measurements were averaged within soil texture grids. An average of 21.8 EC_a points and 4.4 sampling points for soil chemical properties resided within each polygon. Geostatistical analyses were conducted on EC_a and georeferenced samples for soil properties using ESRI (Arcview® GIS 3.2a, Redlands, CA). Because soil samples were collected at the 0–15-cm depth, Pearson correlation coefficients were calculated only for soil properties (% sand, % silt, % clay, SOC, N, P, K, Mg, Ca, CEC_{est}, pH, and buffer pH) and $EC_{a\text{-}30}$ (30-cm depth). Isotropic semivariograms were calculated in Gamma Design software (GS+®, Plainwell, MI) at both depths. The semivariogram model and its parameters provide a quantitative expression of spatial structure for the measured property, including the distance over which samples are correlated (range), the amount of microscale variability, the maximum variance between sampling points, and the overall strength of the spatial correlation (Oliver and Webster 1991). Exponential or spherical semivariograms models that exhibited the highest r^2 as evaluated in GS+® were used for parameter estimation. The range of the spatial relationship measures the distance beyond which two observations are spatially uncorrelated, and the sill is theoretically equal to the maximum variance of the sampled population at large separation distances (Oliver and Webster 1991). The relative structural variability (RSV) is the ratio of the fractional sill to the total sill (Robertson, Crum, and Ellis 1993), which indicates the percentage of the variability that is spatially structured.

Analysis of variance for nested classifications was performed to detect differences among treatments (Figure 1, Table 2) for all soil properties using the general linear models procedure of the Statistical Analysis System (Little, Stroup, and Freund 2002). We assumed each plot (more than 100 years in duration) as a distinct "management zone" for EC_a and soil properties. Soil $EC_{a\text{-}30}$ and extractable P vs. clay content were analyzed across cropping systems (n = 6).

RESULTS AND DISCUSSION

Geostatistical Parameters

The semivariogram models for EC_a were significant in 9 of the 13 plots for $EC_{a\text{-}30}$ and 12 of the 13 plots for $EC_{a\text{-}90}$ (Table 3). In most cases, semivariograms were best described using exponential models, followed by spherical semivariogram models. The range of spatial correlation, which measures the distance beyond which two observations are spatially uncorrelated, varied among the plots (7 to 95 m and 6 to 116 m for $EC_{a\text{-}30}$ and $EC_{a\text{-}90}$, respectively. The relative structural variability (RSV) values exceeded 59% in 9 of 13 plots for $EC_{a\text{-}30}$ and in 72% in 12 of 13 plots for $EC_{a\text{-}90}$. For $EC_{a\text{-}30}$ the RSV average was 74% and for $EC_{a\text{-}90}$, the RSV average was 87%, indicating that most of the variation in the EC_a was attributable to factors other than measurement error. One of the possible reasons that $EC_{a\text{-}30}$ was lower RSV than $EC_{a\text{-}90}$ is that erratically distributed crop residues from conservation tillage management can generate different volumetric water contents and consequent different EC_a values (Johnson et al. 2001). However, Shaw and Mask (2003) evaluated residue effect on conservation tillage practices on EC_a and concluded that residue had minimal effect on EC_a values. Another source of error could be variation due to different crop residues (cotton, soybean, and corn) among different plots and the presence of the crimson clover cover crop planted 40 days before EC_a readings in 7 of the 13 plots. However, the clover did not present much biomass at this early stage of development. Collectively, however, all these factors may have lead to variations in soil moisture that affected shallow EC_a readings. Between August and October 1999, precipitation was 40% below the long-term average, leading to dry soil conditions during EC_a readings. Sudduth, Drummond, and Kitchen (2001) found EC_a has significant temporal variability, primarily as the result of changes in soil profile moisture amount and distribution. The semivariograms for both depths suggest that a complete characterization of this long-term field

Table 3. Isotropic semivariogram parameters for apparent electrical conductivity (EC_a) at two depths (30- and 90-cm) for each plot in the Old Rotation experiment, Auburn, AL (n = 2039)

		Electrical conductivity at 30-cm ($EC_{a\text{-}30}$)					Electrical conductivity at 90-cm ($EC_{a\text{-}90}$)				
Plot	n[a]	Model[b]	Range (m)	Sill ($mS^2\ m^{-2}$)	RSV[c] (%)	r^2	Model	Range (m)	Sill ($mS^2\ m^{-2}$)	RSV (%)	r^2
1	151	s	41	0.5	91	0.93	e	67	2.1	99	0.93
2	155	e	41	0.6	83	0.84	s	40	2.3	94	0.95
3	146	e	13	0.3	67	0.91	e	116	2.2	92	0.98
4	169	e	9	0.5	69	0.95	e	14	0.6	72	0.99
5	152	—	—	—	—	ns[d]	e	6	0.5	81	0.90
6	152	—	—	—	—	ns	—	—	—	—	ns
7	136	e	9	0.2	94	0.97	e	6	0.4	100	0.93
8	180	e	91	0.4	69	0.95	e	49	1.7	80	0.93
9	160	—	—	—	—	ns	e	98	2.1	89	0.96
10	153	e	91	0.8	59	0.89	e	11	1.1	90	0.95
11	99	—	—	—	—	ns	e	89	2.5	81	0.78
12	213	e	95	1.1	69	0.95	e	17	1.4	78	0.93
13	173	e	7	0.8	62	0.81	e	40	6.3	89	0.94

[a] n, EC_a readings.
[b] e, Exponential model; s, spherical model.
[c] RSV, relative structural variability.
[d] ns, Not significant at the 0.1 level.

experiment was done properly, reducing the variance to levels that approach precision in the laboratory (Wright 1998).

Correlation Analysis and Spatial Structure

The sampling grid for clay content, sand content, $EC_{a\text{-}30}$, $EC_{a\text{-}90}$, SOC, N, extractable P, and pH is shown in Figure 3. Soil EC_a data were lower than values in other studies (Mueller et al. 2003) (range: 1.6–4.9 and 3.6–8.1 mS m^{-1} for $EC_{a\text{-}30}$ and $EC_{a\text{-}90}$, respectively). The $EC_{a\text{-}30}$ measurements were reasonably well correlated with $EC_{a\text{-}90}$ measurements ($r = 0.50$ and significant at $P < 0.01$)(data not shown). In this study, $EC_{a\text{-}30}$, clay content, and

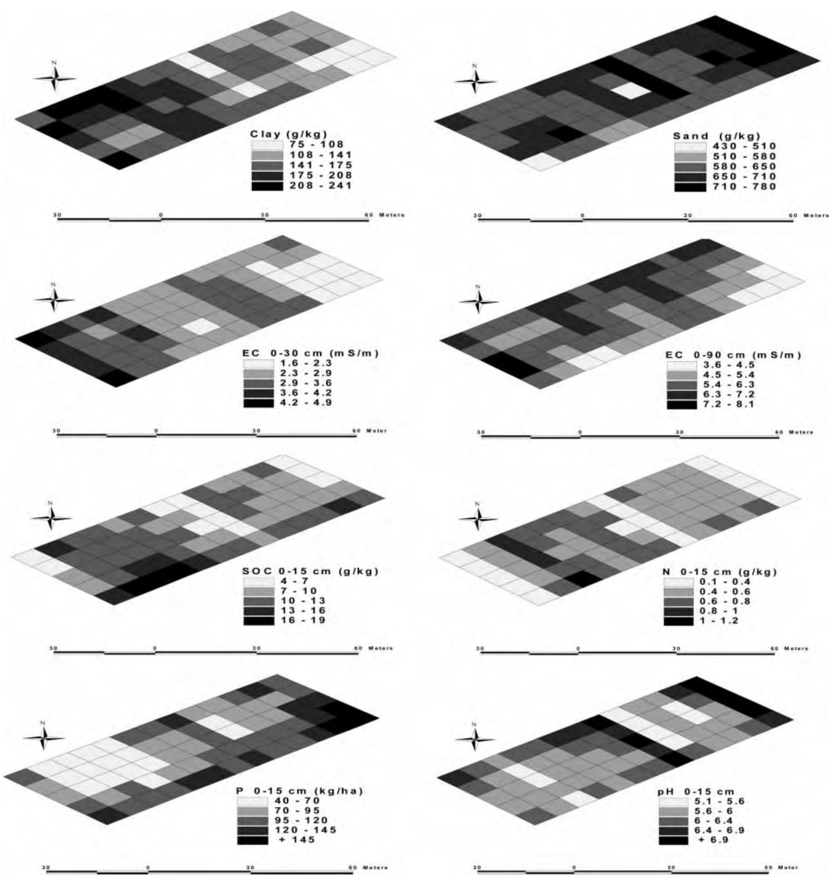

Figure 3. Clay content (0–15-cm), sand content (0–15-cm), apparent electrical conductivity (EC, 30- and 90-cm depths), soil organic carbon (SOC) at 0–15-cm, soil nitrogen at 0–15-cm, phosphorous (P) at 0–15-cm, and pH at 0–15-cm values by grid (7.5 × 6.9 m) in the Old Rotation experiment, Auburn, AL (n = 65).

CEC_{est} were all documented as positive loading factors. Apparent soil electrical conductivity consists of two mechanisms: (a) the contribution of the solid soil particles mainly related with exchangeable cations and (b) the contribution of the soil solution (Nadler and Frenkel 1980). Cations regularly related with binding sites on the soil particles (e.g., Ca, Mg, or K) can influence soil EC_a by changing electrical conductivity of soil particles (EC_s). However, in field conditions, the influence that changing levels of soil cations have on EC_s is minor compared with the influence associated with changes in soil texture and volumetric water content (Lund et al. 1999). In general, direct relationships between $EC_{a\text{-}30}$ and exchangeable K, Mg, Ca, pH, and *B*pH were weak or nonsignificant (Table 4). Multivariate relationships between soil properties and $EC_{a\text{-}30}$ were described with a five-variable multiple regression model ($R^2 = 0.62$) (Table 5). Clay content was the most important single variable in the model followed by N, Mg, *B*pH, and P.

Apparent soil $EC_{a\text{-}30}$ was more highly correlated with clay ($r = 0.58$, $P \leq 0.01$) than other measured soil properties. Clay content affects EC_a because of the water film and exchangeable cations associated with clays (Mueller et al. 2003). In the Old Rotation there is a variation in soil texture; a thin cap of unconsolidated Coastal Plain sediments overlies finer textured, highly weathered Piedmont soils. Patterns in $EC_{a\text{-}30}$ values were found to be related to these two soil types. The Coastal Plain sediment (sand > 58%) is located in the northeastern side of the experiment (Figure 3). For the Piedmont soils, which have greater clay content, higher values of $EC_{a\text{-}30}$ were observed, indicating a good relationship between clay content and $EC_{a\text{-}30}$ data related to soil variability.

Correlation coefficients between soil properties and EC_a ranged from 0.01–0.58 (Table 4). Correlations were strong with clay, sand, and *B*pH, likely due to texture determinations solely from surface soil (0–15-cm sampling). Only three of nine correlations between $EC_{a\text{-}30}$ and soil chemical properties were significant ($P \leq 0.05$). Negative correlations were observed between soil EC_a and some nutrient concentrations, mainly between $EC_{a\text{-}30}$ and P, which could not be caused by the direct influence of these ions on electrical conductivity. The lack of physical reasons for the negative relationship between these soil chemical properties and EC_a shows that there are other factors masking the effect of these exchangeable nutrients on EC_a in the soil. Soil $EC_{a\text{-}30}$ being negatively correlated with P may be attributable to $EC_{a\text{-}30}$ increasing with clay content. It is likely that the high clay content and subsequent enrichment in quothite (FeOOH) and gibbsite ($AlOH_5$), fixed more P and as a result P extracted with the Mehlich-1 method was less (Mehlich 1953). The relationship between clay content and P was highly negative ($r = 0.65$, $P \leq 0.01$).

Individually, total nitrogen (N) and SOC had no relationships with $EC_{a\text{-}30}$. As expected, these two soil chemical properties (SOC and N) were significantly correlated ($r = 0.71$, $P \leq 0.01$). Clay content had a positive correlation with SOC and N ($r = 0.34$ and $r = 0.35$ for SOC and N, respectively

Table 4. Pearson correlation coefficients for apparent soil electrical conductivity (EC_a) at 30-cm depth, soil texture (0–15-cm), and soil chemical properties (0–15-cm depth) in the Old Rotation experiment, Auburn, AL (n = 65)

Soil properties[a]	EC_{a-30}	$Sand_{(0-15)}$	$Silt_{(0-15)}$	$Clay_{(0-15)}$	$SOC_{(0-15)}$	$N_{(0-15)}$	$P_{(0-15)}$	$K_{(0-15)}$	$Mg_{(0-15)}$	$Ca_{(0-15)}$	$CEC_{(0-15)}$	$pH_{(0-15)}$
$Sand_{(0-15)}$	−0.35**	—	—	—	—	—	—	—	—	—	—	—
$Silt_{(0-15)}$	−0.04	−0.76**	—	—	—	—	—	—	—	—	—	—
$Clay_{(0-15)}$	0.58**	−0.69**	0.05	—	—	—	—	—	—	—	—	—
$SOC_{(0-15)}$	0.18	−0.51**	0.39**	0.34**	—	—	—	—	—	—	—	—
$N_{(0-15)}$	−0.08	−0.36**	0.18	0.35**	0.71**	—	—	—	—	—	—	—
$P_{(0-15)}$	−0.43**	0.39**	−0.16	−0.65**	−0.09	−0.31**	—	—	—	—	—	—
$K_{(0-15)}$	−0.13	0.09	0.18	−0.35**	−0.11	−0.13	0.29**	—	—	—	—	—
$Mg_{(0-15)}$	0.22	0.05	−0.17	0.01	0.13	−0.26	0.40**	−0.17	—	—	—	—
$Ca_{(0-15)}$	0.10	−0.19	0.10	0.06	0.50**	0.04	0.46**	−0.04	0.72**	—	—	—
$CEC_{est(0-15)}$	0.29*	−0.40**	0.19	0.21	0.67**	−0.07	0.24	0.03	0.54**	0.88**	—	—
$pH_{(0-15)}$	−0.01	0.41**	−0.28	−0.32**	−0.47**	−0.45**	0.53**	0.03	0.71**	0.39**	0.15	—
$B pH_{(0-15)}$	−0.29*	0.47**	−0.36**	−0.31**	−0.41**	0.63**	0.46**	−0.12	0.54**	0.24	−0.23	0.63**

[a]$EC_{a\text{-}30}$ = apparent soil electrical conductivity at 30-cm depth; SOC = soil organic carbon; N = total nitrogen; CEC_{est} = cation exchange capacity; *B*pH = buffer pH.

*, **Significant (test for |r| = 0) at the 0.05 and 0.01 probability levels, respectively.

Table 5. Stepwise multiple regression (n = 55) model for apparent soil electrical conductivity ($EC_{a\text{-}30}$) data collected in the Old Rotation experiment, Auburn, AL

Shallow EC_a (0–30-cm)			
Independent variable[a]	Parameter estimate	t Value	Model R^2
Intercept	35.56	4.79***	—
Clay content	0.069	3.24**	0.34
N	−12.27	−4.20***	0.43
*B*pH	−4.34	−4.49***	0.49
Mg	0.005	4.50***	0.59
P	0.005	−2.19*	0.62

[a]SOC = soil organic carbon; N = total nitrogen; *B*pH = buffer pH.
*, **, ***Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

[$P \leq 0.01$]). On the other hand, sand content had a negative correlation with SOC and N ($r = 0.51$ and $r = 0.36$ for SOC and N, respectively [$P \leq 0.01$]). These results agree with Havlin et al. (1990), who reported SOC and N were directly proportional to clay content. Bajracharya, Lal, and Kimble (1997) suggested that a strong association between microaggregates and clay keeps SOC more stable, resistant, and protected from decomposition. Soil organic C had a strong correlation with Ca and CEC_{est} ($r = 0.50$ and $r = 0.67$ for Ca and CEC_{est}, respectively [$P \leq 0.01$]).

Estimated cation exchange capacity (CEC_{est}) was correlated with EC_a ($r = 0.71$, $P \leq 0.01$). This is likely due to cations and clay content positively affecting both CEC_{est} and EC_a (Table 4, Figure 3).

Highest correlations for pH were found with SOC, N, Mg, Ca, P, and sand content. The negative relationship between SOC and N to pH may be due to decomposition of organic residue increasing soil acidity. The relationship between extractable Mg and Ca with pH ($r = 0.71$ and $r = 0.39$, for Mg and Ca, respectively [$P \leq 0.01$]) is attributed to removal of cations in exchange for H^+ (Lindsay 1979). The extractable base Ca was well correlated with SOC but not with Mg. Calcium was the strongest basic cation correlated with CEC_{est} ($r = 0.88$, $P \leq 0.01$), indicating that in the Old Rotation Ca is the most important cation for exchange capacity.

Franzluebbers (2002) developed a concept of using a SOC stratification ratio as an indicator of dynamic soil quality. This author concluded that a good SOC stratification ratio is between 2 to 3, depending on soil type and climatic conditions. The overall average SOC stratification ratio that Siri-Prieto et al. (2002) found in the Old Rotation after 98 years was 1.31, closer to values found with conventional tillage than for conservation tillage as reported by Franzluebbers (2002). This indicates that the Old Rotation is only in the beginning stages of change regarding SOC and associated properties. These results agree with the positive correlation found between the 0–5 and 5–15-cm depths for all individual soil test properties, indicating the impact of conventional tillage for 98 years (data not shown).

The relatively small plots (42 by 6.5 m) in the Old Rotation contained considerable spatial variation for pH and some applied nutrients such as P (Figure 3). This demonstrates the difficulties of conducting agronomic experiments on heterogeneous soil and the need for monitoring spatial nutrient distributions, even on small plots, which facilitate more precise applications of nutrients and lime.

Long-Term Management Effects

With the exception of Ca and CEC_{est}, all soil parameters measured were significantly different among cropping systems (Table 6). It is interesting to note that the relationships between $EC_{a\text{-}30}$ and clay content, sand content, and P improved dramatically when combined over cropping systems ($n = 6$) (Table 6). A highly significant correlation ($r = 0.99$, $P \leq 0.01$) was observed between $EC_{a\text{-}30}$ and % clay using a second-order polynomial equation (Figure 4). Kitchen, Sudduth, and Drummond (2000) reported a second-order polynomial equation related EC_a to percent clay (0–15-cm) with an $r^2 = 0.71$ for a Typic Udipsammnet in Missouri. Similar to percent clay, in the Old Rotation, P fit best using a second-order polynomial equation ($r = 0.89$, $P \leq 0.01$) when analyzed across cropping systems ($n = 6$).

In the Old Rotation, clay content was the principal factor controlling EC_a. Despite more than 100 years with different management practices resulting in differences in SOC and N among plots, there was no direct relationship between EC_a and these soil chemical properties.

Averaged across cropping systems (except for continuous cotton + N), the relationship between clay content and SOC was improved when analyzed in univariate data. These results agree with studies by Havlin et al. (1990) with respect to strong relationships among clay content, SOC, and N. In the Old Rotation, SOC and N were strongly affected by cropping systems. Long-term planting of winter legumes and crop rotations significantly improved these soil-quality indicators (SOC and N). The worst system in regard to soil quality and productivity (Mitchell and Entry 1998) was continuous cotton without legumes, following by continuous cotton plus N. The best system was the most intensive (cotton–legume–corn–small grain–soybean). Havlin et al. (1990) concluded that the positive effects of crop rotations on physical, chemical, and biological soil properties are related to higher carbon inputs and diversity of plant residues returned to soils. Entry et al. (1996) found that after 99 years of management practices in the Old Rotation, winter legumes increased SOC and N in soil, which ultimately contributed to higher cotton yields. In the past, under conventional tillage,

Table 6. Apparent soil electrical conductivity (EC_a) (0–30-cm), soil texture (0–15-cm), and soil chemical properties (0–15-cm) affected by cropping systems in the Old Rotation experiment, Auburn, AL

	Cropping systems[a]						
Soil properties[b]	CC	CC + N	CC + leg	2-yr Rot. + leg	2-yr Rot. + leg + N	3-yr Rot. + leg + N	Pr > F
Sand (g kg^{-1})	721	620	685	629	621	631	0.0017
Clay (g kg^{-1})	113	199	137	150	168	181	0.0001
$EC_{a\text{-}30}$ (mS m^{-1})	2.8	4.3	2.6	2.7	3.0	3.3	0.0001
SOC (g kg^{-1})	6.3	9.8	9.6	8.9	11.2	13.4	0.0013
N (g kg^{-1})	0.23	0.35	0.62	0.56	0.63	0.75	0.001
P (kg ha^{-1})	137	98	111	95	77	69	0.001
K (kg ha^{-1})	165	159	176	185	162	131	0.0127
Mg (kg ha^{-1})	229	189	133	127	142	165	0.0043
Ca (kg ha^{-1})	1223	1189	1017	895	894	1204	ns[c]
CEC_{est} ($cmol_c$ kg^{-1})	6.07	6.50	5.66	5.45	5.61	6.71	ns
pH	7.21	6.16	5.99	6.06	5.73	5.86	0.0001
*B*pH	7.77	7.68	7.70	7.69	7.67	7.64	0.013

[a]CC = continuous cotton (no legume and 0 N).

CC + N = continuous cotton + N applied to cotton (134 kg ha^{-1} yr^{-1}).

CC + leg = continuous cotton + legume (winter cover crop; crimson clover since 1956).

2 yr rot. + leg = 2-yr cotton-corn + legume (winter cover crop; crimson clover since 1956).

2-yr rot + leg + N= 2-yr cotton-corn + legume (winter cover crop; crimson clover since 1956) + nitrogen applied to cotton or corn (134 kg ha^{-1} yr^{-1}).

3 yr rot. + leg + N = 3-yr cotton-corn-small grain/soybean+ legume (winter cover crop; crimson clover since 1956).

+ Nitrogen applied to small grain (67 kg ha^{-1} yr^{-1}).

[b]$EC_{a\text{-}30}$ = apparent soil electrical conductivity at 30-cm depth; SOC = soil organic carbon; N = total nitrogen; CEC_{est} = cation exchange capacity; BpH = buffer pH.

[c]ns = Nonsignificant *F* value at the 0.05 level.

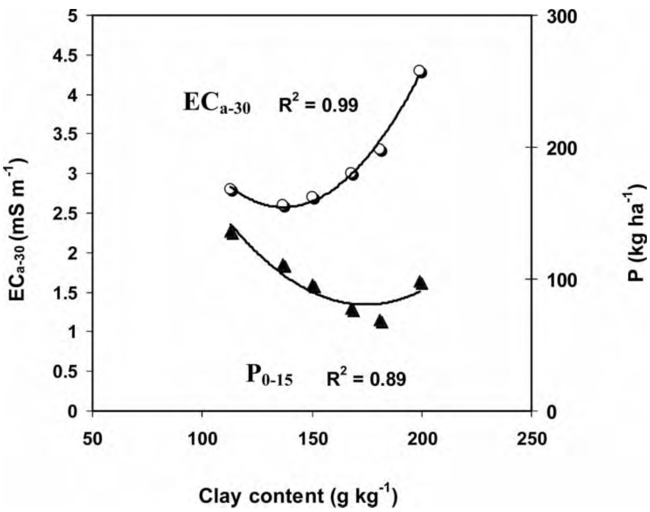

Figure 4. Relationship between clay content vs. soil $EC_{a\text{-}30}$ and extractable phosphorus content (0–15-cm) in the Old Rotation experiment, Auburn, AL. Each point represents means of cropping system (n = 6).

crop rotation benefited cotton yields, and these benefits have improved under conservation tillage (Mitchell, Reeves, Delaney 2001). Siri-Prieto, Reeves, Shaw, Mitchell (2002) found that in the Old Rotation SOC dramatically increased after only 3 years of conservation tillage. Their data confirmed that conservation tillage systems with crop rotation and winter legume cover crops had the largest effect on SOC, but it may take years to reverse the degradation resulting from 99 years of conventional tillage (Siri-Prieto et al. 2002).

The rate of fertilizer P and K applied to the Old Rotation has been the same every year in all-cropping systems (39–56 kg P–K ha^{-1} $year^{-1}$ in the last 43 years). Yields of the more intensive cropping systems have been higher than the less intensive systems (Mitchell and Entry 1998), indicating greater extraction of nutrients from the more intensive rotations. These data show that increased yield in the better rotation treatments has led to greater extraction of P and lower soil P (80 vs. 115 kg ha^{-1} for the three crop rotations compared to the three continuous cotton systems, respectively). Likewise, soil Mg averaged 145 kg ha^{-1} for the three crop rotations vs. 184 kg ha^{-1} for the three continuous cotton systems (Table 6).

CONCLUSIONS

Soil EC_a data at both depths were spatially structured, but $EC_{a\text{-}90}$ presented higher spatial distribution than $EC_{a\text{-}30}$. This difference is likely the result of homogenization of near-surface soil properties following 99 years of conventional tillage management.

Total N and SOC were significantly associated ($r = 0.71$, $P \leq 0.01$) but neither property could be related to $EC_{a\text{-}30}$. Despite dramatic differences in soil N and SOC as a result of more than 100 years of different cropping systems, EC_a was not a good predictor of SOC and N.

Correlations among soil properties improved when cropping systems were analyzed separately. Phosphorous and Mg were inversely related to intensity of cropping systems. Yields of more intensive cropping systems have historically been higher than less intensive systems (Mitchell and Entry 1998), indicating extraction of these nutrients is greater in these systems. In the future, it may be necessary to reconsider the fertilization regime for the various cropping systems in the Old Rotation.

There was considerable spatial variation for pH and some applied nutrients such as P in the relatively small plots of the Old Rotation. This demonstrates the difficulty of conducting fertility experiments on heterogeneous sites. It also suggests that researchers might benefit from using precision agriculture techniques such as grid sampling and variable rate nutrient and lime applications, even at the scale of experiments such as the Old Rotation.

Soil $EC_{a\text{-}30}$ was more highly correlated with clay and P than other soil properties. Soil $EC_{a\text{-}30}$ was negatively correlated with P, perhaps attributable to $EC_{a\text{-}30}$ increasing with clay content. Greater % clay likely resulted in greater P fixation and as a result extractable P was less. With the exception of P, the relatively poor and variable relationships between soil chemical parameters and EC_a established from this intensively sampled study suggest that mapping plant nutrients and SOC using EC_a is problematic because of dependence with clay and water content.

ACKNOWLEDGMENTS

Reference to a company trade name is for specific information only and does not imply approval or recommendation of the company by the USDA or Auburn University.

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