A Multivariate Approach for High-Resolution Soil Survey Development

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Abstract: First-order soil surveys (scales >1:12,000) are essential for detailed land use assessment. Recently developed technologies depicting landscape variability at high resolution are useful for first-order survey development. Our objective was to compare a first-order soil survey created using conventional techniques versus a multivariate first-order survey developed using terrain attributes calculated from digital elevation models and electrical conductivity (EC) mapping. Two research sites (Macon [9 ha] and Dale [8 ha]) were located in the Coastal Plain physiographic region of Alabama, and first-order soil surveys (scale >1:12,000) were generated using conventional techniques. Soils are largely Aquic, Oxyaquic, and Typic Paleudults at the Macon site and Typic Kandiudults that differ in particle size family at the Dale site. Elevation data were collected using real-time kinematic global positioning system, terrain attributes were calculated, and field-scale EC data were collected. Three principal factors described 81% and 80% of the terrain and EC variability for the Macon and Dale sites, respectively, and fuzzy k-means clustering of principal factor scores was used to create multivariate zones. Random pedon sampling was used to compare techniques, and a rigid similar-dissimilar rule (one-class) was used for accuracy assessment. Probabilities of success (p) for observing the named soil within a map unit for the multivariate zone approach averaged 50% and 76% for the Macon and Dale sites, respectively, which was slightly less than the conventional approach. Estimated errors and confidence interval calculation indicate that for these Alabama Coastal Plain landscapes the overall accuracy of the two approaches was similar.

Key words: Order 1 soil survey, ultisols, Coastal Plain, Kandiudults.

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The soil-landscape paradigm (Hudson, 1992), based on the soil-forming factors equation (Jenny, 1941), describes relationships used for soil survey development. The paradigm states that within a soil-landscape unit, the soil-forming factors interact to form similar soils, whereas different soils are found in adjoining soil-landscape units that are dissimilar (Hudson, 1992). Terrain (relief) is a soil-forming factor that is highly related to soil variability in landscapes with similar parent materials, and identifiable terrain components are used to map soil landscapes. In addition, many researchers have investigated relationships between terrain attributes and soil properties (Moore et al., 1993; Brubaker et al., 1993).

Digital elevation modeling and geophysical surveys (e.g., ground penetrating radar and electrical conductivity [EC] mapping) are two methods used to evaluate landscape and soil spatial variability (Fraisse et al., 2001; Kitchen et al., 2003a). Digital elevation models are rasterized grid elevation values on fixed intervals. Terrain attributes including slope, aspect, plan, and profile curvature and indices related to soil wetness are calculated from a digital elevation model (DEM) (Moore et al., 1993). Relationships between topography and soil properties have been widely studied and, from a composite perspective, can provide a basis for taxonomic-based soil survey applications. Similarly, individual soil properties including organic matter content, A and B horizon thickness, pH (Kreznor et al., 1989), soil texture, base saturation, cation exchange capacity (CEC) (Brubaker et al., 1993), organic carbon (Malo et al., 1974), and aggregate stability (Pierson and Mulla, 1990) have all been found to systematically vary with topographic position.

Soil property variability can sometimes be depicted using field-scale soil EC mapping (Sudduth et al., 2003). Field-scale EC data collection can be performed with noncontact electromagnetic induction or direct contact EC sensors (Sudduth et al., 2003). Direct contact sensor methods use cart-mounted Coulter electrodes pulled through the soil to obtain apparent electrical conductivity (EC_a) data at estimated depths of 0 to 30 and 0 to 90 cm. Georeferenced EC_a data are used to generate EC surveys, which are then related to field-scale soil variability (Shaw and Mask, 2003; Sudduth et al., 2003). Field-scale EC is dependent on several soil properties including soil-water content, texture, and temperature (Rhoades et al., 1989; Inman et al., 2002). Electrical conductivity data have been correlated with soil clay content (Williams and Hoey, 1987; Shaw and Mask, 2003), sand deposition depth (Kitchen et al., 1996), claypan depth (Doolittle et al., 1994), water content (Kachanoski et al., 1988), chemical properties (Bishop and McBratney, 2001), and drainage class (Kravchenko et al., 2002). In summary, it is well documented that DEM and EC mapping can be useful for evaluating soil variability across landscapes.

Efforts have been made to develop soil surveys using multivariate data including terrain attributes, geological surveys, remote sensing, and EC data. Zhu et al. (2001) developed a soil-landscape inference model (SoLIM) combining fuzzy logic with expert knowledge; SoLIM uses a similarity model in a raster format for digital representation of soils. Using fuzzy logic and expert knowledge, a pixel is assigned to multiple soil classes, and each soil class within that pixel is assigned a weight based on class membership. Through automated soil inference, and using the concepts outlined by Jenny (1941) and Hudson (1992), a raster soil survey is created, and spatially detailed maps of soil taxonomic class or soil property data can be developed.

Similarly, Van Alphen and Stoorvogel (2000) created first-order survey (1:5,000) for two fields in the Netherlands, and fuzzy k-means classification was used to derive class membership values. After class membership was assigned, the layers were combined to create a confusion index map. Soil-landscape

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unit boundaries were placed along confusion index values equal to one as these values suggest transitions between classes. The units were then assigned representative soil profiles best matching the characteristics of that class. In comparison, a conventional soil survey generated more classes in both fields, suggesting the efficiency of multivariate data classification for soil-landscape unit delineation. Other studies have also used fuzzy k-means clustering to compare the distribution of soil classes (Young and Hammer, 2000), delineate zones of crop productivity (Kitchen et al., 2003b), and characterize the spatial variation of soil chemical properties (Schepers et al., 2004).

Order 2 (1:12,000–1:24,000) soil surveys do not offer a high-resolution depiction of the soil continuum often required for detailed land use planning and site-specific environmental assessment and management. Order 1 (>1:12,000) soil surveys are created at a higher resolution when more detailed depiction of soil variability is required (Soil Survey Division Staff, 1993). However, the observation and sampling intensity renders them expensive and time consuming to develop. The development of Order 1 soil surveys may be facilitated by the use of technologies that depict landscape variability and soil properties at relatively higher resolution. Researchers have utilized these technologies and related clustering techniques for applications such as developing precision agriculture management zones (e.g., Kitchen et al., 2003b; Kitchen et al., 2005; Moral et al., 2010), and several studies have related terrain attributes and EC data to specific soil properties (described above); no study that we are aware of has compiled these specific data for creating taxonomic based soil-landscape units for Order 1 survey development.

The objective of this research was to investigate digital elevation modeling, terrain attribute computation, soil EC mapping, and multivariate clustering of these data for developing soil-landscape units (termed multivariate zones) in southeastern United States (Alabama) Coastal Plain landscapes. The southeastern U.S. Coastal Plain provides an ideal location for conducting this study as soils are largely related to geomorphic surface, but substantial variability within soil landscapes occurs (Shaw et al., 2004). Landscape zones were used to guide taxonomic-based, first-order soil survey sampling efforts, and a comparison was made between a soil survey developed using conventional techniques and the multivariate zone delineation approach. Relationships between investigated soil properties and EC and terrain attributes were also evaluated.

MATERIALS AND METHODS

Site Description

Two research sites were located in the Coastal Plain physiographic province of Alabama. Site 1 was located at the Alabama Agricultural Experiment Station, E. V. Smith Research Center in Macon County, Alabama, where parent materials are mid to late Pleistocene age fluvial sediments. This site is a 9-ha row-crop field in a cotton (*Gossypium hirsutum* L.)–corn (*Zea mays* L.) rotation, and soils are predominantly Paleudults (Table 1). Site 2 was located in Dale County, Alabama, where parent materials are Eocene age fluviomarine sediments. This site is an 8-ha row-crop field in a cotton-peanut (*Arachis hypogaea*) rotation, and soils are predominantly Kandiudults.

First-Order Soil Survey Methods

First-order soil surveys were developed for both sites (Figs. 1 and 2 for the Macon and Dale sites, respectively). For this survey creation, 13 observations were made at the Macon site (density of one observation per 0.69 ha), and 18 observations (one observation per 0.44 ha) were made at the Dale site. To facilitate this, georeferenced (Trimble® Pro XRS global positioning system [GPS]; Trimble,[1] Sunnyvale, CA) soil observations were overlaid onto the maximum downhill slope (MDS) map (using ArcGIS; ESRI,[1] Redlands, CA) for assistance in polygon creation, and map units were delineated based on soils and slope class. For taxonomic correlation of units (naming), the predominance of soils observed through random observations was used (described below). Slope phases for map units at the Macon site for this soil survey were set at relatively fine increments of 0% to 2%, 2% to 4%, and 4% to 6%. Slopes were steeper on the Dale site, and slope units were established at 0% to 2%, 2% to 6%, and 6% to 12%. This resulted in the creation of polygons at high resolution (smallest delineation was 0.57 ha at Macon site and was 0.18 ha at Dale site), with a resulting scale greater (more detailed) than 1:12,000 (Order 1).

TABLE 1. Classification of Soils Used in Map Unit Consociation and Complex Naming

Series	Family
Summerton	fine, kaolinitic, thermic Typic Paleudults
Noboco	fine-loamy, siliceous, subactive, thermic Oxyaquic Paleudults
Noboco (taxadjunct)†	fine, kaolinitic, thermic Oxyaquic Paleudults
Duplin	fine, kaolinitic, thermic Aquic Paleudults
Goldsboro	fine-loamy, siliceous, sub-active, thermic Aquic Paleudults
Faceville	fine, kaolinitic, thermic Typic Kandiudults
Orangeburg	fine-loamy, kaolinitic, thermic Typic Kandiudults
Benevolence	coarse-loamy, kaolinitic, thermic Typic Kandiudults

†No named series.

Soil samples were obtained from horizons of selected typical pedons for laboratory characterization (six pedons for Macon site, four pedons for Dale site) to facilitate classification of observations and correlation of map units to a taxonomic class (Soil Survey Staff, 2003). In addition, during random observations for statistical analyses (detailed below), 45 and 39 sub-soil horizon samples for the Macon and Dale sites, respectively, were analyzed in the laboratory for texture to facilitate soil taxonomic placement. In addition, grid samples (0.4 ha) for surface (0–30 cm) soil texture determination were collected and analyzed in the laboratory (Kilmer and Alexander, 1949). These data were used for map unit phase determination (surface texture) and additionally for relating surface soil texture with EC and terrain attribute data.

Laboratory Analysis

For type pedon characterization, samples collected by horizon were air dried and ground to pass a 2-mm sieve. Soil texture was analyzed using the pipette method (Kilmer and Alexander, 1949). Cation exchange capacity and base saturation were measured by the ammonium acetate (pH 7) method using an autoextractor (Soil Survey Laboratory Staff, 1996). Extractable aluminum (Al) was determined using 1 *M* KCl with an autoextractor (Soil Survey Laboratory Staff, 1996), and Al concentrations were determined via titration. Extractable Al was combined with base measurements from the CEC method to determine effective CEC (Soil Survey Laboratory Staff, 1996).

[1]Reference to trade or company name is for specific information only and does not imply approval or recommendation of the company by Auburn University or the Alabama Agricultural Experiment Station to the exclusion of others that may be suitable.

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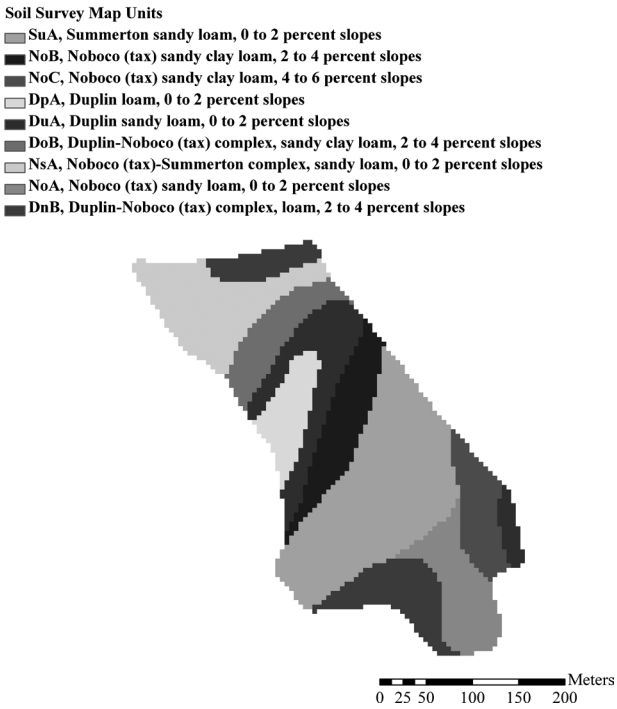

FIG. 1. First-order soil survey for 9-ha Macon County, Alabama, research site.

Digital Elevation Modeling and Terrain Attribute Computation

Real-time kinematic GPS elevation data were collected on 1-s time intervals using a base station and GPS receiver (Trimble). Five-meter DEM were generated for both sites using a finite difference interpolation technique in ArcInfo (ESRI) (topo to raster command). Terrain attributes of MDS (ERDAS Imagine; Leica Geosystems GIS & Mapping, Atlanta, GA), profile and planimetric curvature (ArcGIS; ESRI), and flow accumulation (ArcHydro; ESRI) were calculated from the DEM. Catchment area (flow accumulation × cell area), specific catchment area (flow accumulation × cell size), and compound topographic index (CTI) (Moore et al., 1993) were calculated from primary terrain attributes (ArcGIS; ESRI).

Field-Scale Electrical Conductivity Mapping

Electrical conductivity data for both fields were collected (Veris 3100; Veris Technology,[1] Salina, KS). This method uses direct contact sensors to measure soil electrical resistivity, which is converted to apparent EC (EC_a) (mS m^{-1}). Apparent EC_a data were collected on 1-s intervals at speeds between 2.2 and 4.4 m s^{-1}, and estimated depths of data resolution are 0 to 30 cm ($EC_{a(0–30\ cm)}$) and 0 to 90 cm ($EC_{a(0–90\ cm)}$) (Veris Technologies, 2003). Electrical conductivity data were collected in 2 subsequent years at the Dale site, and only 1 year at the Macon site. Data were collected in winter/spring to have adequate soil moisture for sufficient Coulter contact.

Conductivity data were surfaced to 5-m grids using kriging on a 2 × 2 local grid with weights based on exponential or spherical modeling of isotropic semivariance. The percentage of nugget compared with total semivariance (nugget + sill) is often used to measure the strength of spatial dependence (Cambardella et al., 1994). If the nugget (related to microscale or experimental variability) is a small portion of total semivariance, the property possesses a stronger spatial dependence. Low values of nugget to total semivariance (3%–10% for the Macon site and 13%–26% for the Dale site) suggest high spatial dependence for these EC_a data, with a range of correlation of approximately 100 m.

Multivariate Data Analysis

Correlation ($p \leq 0.05$) between EC, terrain attributes, and surface (0–30 cm) soil texture (from grid points) was performed in SAS (SAS Institute, Cary, NC). Mean shallow and deep EC_a was calculated on a 3 × 3 matrix surrounding surface soil texture grid sampling points. Correlation ($p \leq 0.05$) between 5-m surfaces of EC and terrain attributes was also performed.

Electrical conductivity, elevation, and terrain attribute (profile and planimetric curvatures, flow accumulation, and CTI) layers were combined into one grid file and were normalized (0–100) to account for scale differences between data. Factor analysis (method = principal components) was performed on normalized data layers before the clustering procedure, and factors were selected for k-means clustering that explained 80% of the cumulative variation. Three factors were used for zone creation at both the Macon and Dale County sites (Table 2), and the resulting factor scores were used for fuzzy k-means clustering.

Multivariate Clustering Procedure/Zone Development

The Management Zone Analyst software (Fridgen et al., 2004), which uses a fuzzy k-means clustering algorithm, was used to create multivariate clusters from factor scores. Details are found in Fridgen et al. (2004), but summarizing their approach, the method assigns membership into multiple classes using three matrices: (i) the data to be classified matrix (Y), (ii) a cluster centroid matrix (V), and (iii) a fuzzy membership matrix (U) (Fridgen et al., 2004). A sum of squared errors determines the fuzzy membership matrix (U), and squared difference between an original data set observation (Y) and a cluster centroid (V) is calculated as (Fridgen et al., 2004):

$$(d_{ik})^2 = ||y_k - v_i||^{\ 2} = (y_k - v_i)'\ \mathrm{A}(y_k - v_i) \qquad (1)$$

where y_k is the data observation k, v_i is the centroid of the cluster i, and A is a positive normalizing weight matrix of

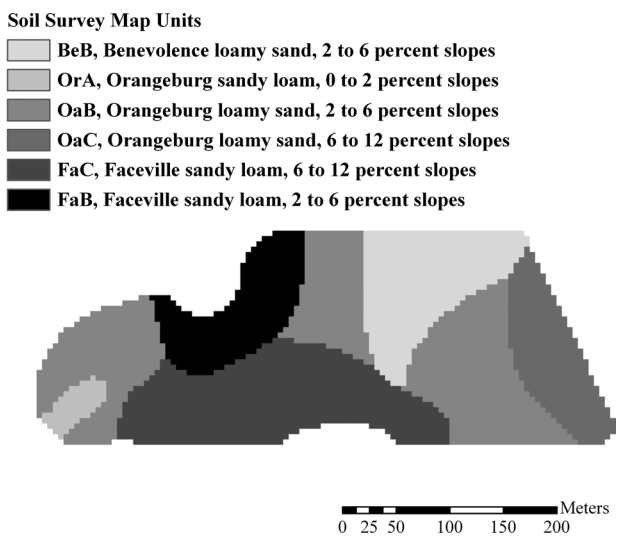

FIG. 2. First-order soil survey for 8-ha Dale County, Alabama, research site.

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TABLE 2. Principal Factor Loadings, Eigenvalues, and Explained Variance for the First Three Principal Factors Developed From Electrical Conductivity, Elevation, Profile and Planimetric Curvatures, Flow Accumulation, and Compound Topographic Index Values for 8-ha Dale County and 9-ha Macon County, Alabama, Research Sites

Soil Landscape Property	Factor 1	Factor 2	Factor 3
Dale County			
$EC_{a(0–30\ cm)}$ Year 1	0.76	0.43	0.08
$EC_{a(0–90\ cm)}$ Year 1	0.92	0.31	0.01
$EC_{a(0–30\ cm)}$ Year 2	0.87	0.34	0.09
$EC_{a(0–90\ cm)}$ Year 2	0.93	0.19	0.00
Elevation	0.84	−0.02	−0.12
Profile curvature	−0.45	0.46	0.60
Planimetric curvature	0.43	−0.65	0.50
Flow accumulation	−0.45	0.59	0.31
Compound topographic index	−0.48	0.67	−0.31
Eigenvalue	4.56	1.86	0.83
Cumulative explained variance (%)	0.51	0.71	0.80
Macon County			
$EC_{a(0–30\ cm)}$	−0.10	0.93	0.01
$EC_{a(0–90\ cm)}$	−0.20	0.92	0.02
Elevation	−0.84	−0.24	−0.22
Profile curvature	0.76	−0.11	0.57
Planimetric curvature	−0.79	−0.15	0.29
Flow accumulation	0.70	−0.07	−0.48
Compound topographic index	0.81	0.10	−0.07
Eigenvalue	3.11	1.83	0.7
Cumulative explained variance (%)	0.44	0.71	0.81

size $p \times p$ (Fridgen et al., 2004). In our research, the euclidean similarity measure was used because of relatively equal variances and small covariance following factor analysis. Readers are encouraged to consult Fridgen et al. (2004) for more information.

The minimum number of multivariate clusters generated was set at two, and the maximum number of multivariate clusters was set for three more than the number of map units established in the first-order soil survey. The maximum number of iterations, fuzziness exponent, and convergence criteria were selected as suggested by Fridgen et al. (2004). A fuzziness performance index and normalized classification entropy were generated by the Management Zone Analyst to facilitate selection of the optimum number of multivariate clusters for delineation (Fridgen et al., 2004). Based on these analyses, the optimum number of clusters for the Macon site was six, and three for the Dale site.

The output file was converted to a grid, and multivariate zones were delineated based on multivariate clusters and slope class. Slope units were developed as in the conventional survey. Clusters and slope class layers were overlaid, multivariate zones were developed, and zones smaller than 0.10 ha were removed. Multivariate zones for the Macon and Dale sites are shown in Figs. 3 and 4, respectively. Each multivariate zone was named for the predominant soil (consociation) as determined from random soil observations as described below. If there were equal numbers of observations of two soils within a map unit, then the unit was named as a complex.

Multivariate Zone and Soil Survey Accuracy Assessment

For accuracy assessment of the two approaches, 75 and 57 randomly located pedons were observed at the Macon and Dale sites, respectively. Select sub-soil horizons were analyzed in the laboratory for soil texture (45 and 39 for Macon and Dale sites, respectively) when the observer needed supporting data for soil classification (e.g., separation of a fine versus fine-loamy soil). This resulted in an average of 9 and 10 pedon observations within each soil survey map unit ("n" in Tables 5 and 6) and multivariate zone for the Macon and Dale sites, respectively. One multivariate zone at the Macon site was removed from analyses as it did not have sufficient observations.

Accuracy statistics were calculated by evaluating taxonomic similarity of pedons within each conventional map unit and multivariate zone. Map units were mostly named as consociations based on pedon observations; that is, units were named for the majority soil (series) observed (e.g., see Tables 5 and 6). As mentioned above, in cases where there were equal numbers of two soils observed, the units were named as complexes. Because of the scale of this research, a rigid one-class rule was used to separate similar-dissimilar soils, that is, the soil needed to be in the exact same taxa to be considered similar. The only exception to this was that Kanhapludults pedons were considered the same as Kandiudults at the Dale site.

Soils at the Macon site predominantly differed at the particle size family and sub-group level (related to drainage class). Therefore, fine-loamy soils were considered dissimilar to fine soils, and Typic sub-groups were considered dissimilar to Oxyaquic subgroups, which were dissimilar to Aquic sub-groups. At the Dale site, soils are predominantly Typic Kandiudults that differ in particle size family. Therefore, coarse-loamy soils were considered dissimilar to fine-loamy soils, which were dissimilar to fine soils. Considering this exercise is concentrated

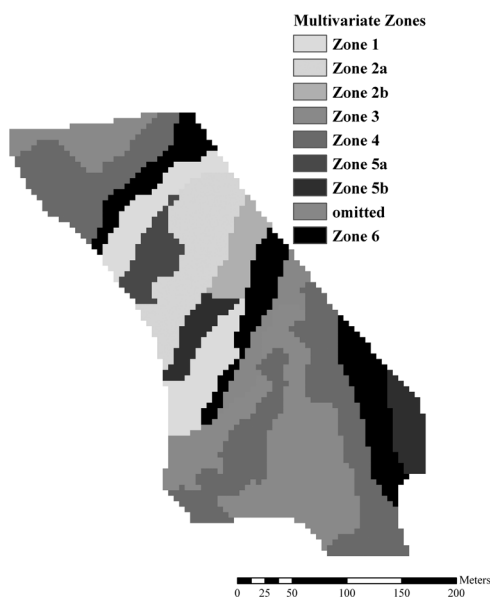

FIG. 3. Multivariate zones for Macon County, Alabama, research site generated using fuzzy k-means clustering of multivariate data including electrical conductivity data, elevation, profile and planimetric curvatures, flow accumulation, and compound topographic index. Final zones developed by overlaying maximum downhill slope over landscape zones. Multivariate zones correlated to soil taxonomic class are listed in Table 5.

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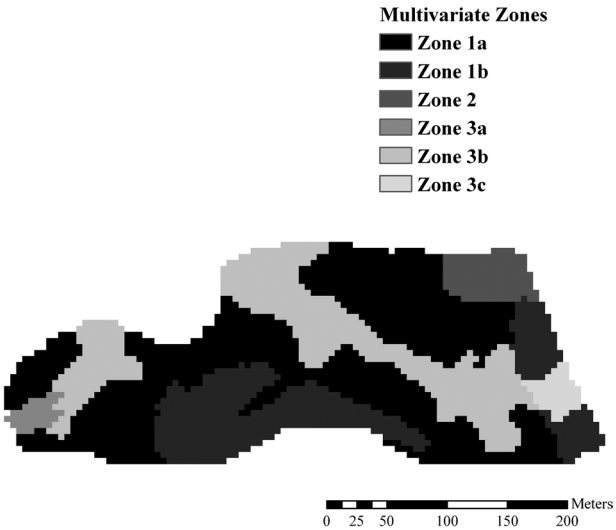

FIG. 4. Multivariate zones for Dale County, Alabama, research site generated using fuzzy k-means clustering of multivariate data including electrical conductivity data from Years 1 and 2, elevation, profile and planimetric curvatures, flow accumulation, and compound topographic index. Final zones developed by overlaying maximum downhill slope over landscape zones. Multivariate zones correlated to soil taxonomic class are listed in Table 6.

on evaluation of the approach as opposed to the actual taxonomic correlation of units, the accuracy for complex units was based on one of the named soils being dissimilar. For example, for the Duplin-Noboco (tax) complex in the Macon site soil survey, three borings of Duplin and three borings of Noboco (tax) were observed in the unit. For accuracy assessment, the unit was considered to be 50% pure ($p = 0.5$, $q = 0.5$).

The survey accuracy assessment approach used was that of Edmonds and Lentner (1986). Binomial expansion was based on the number of successes and failures of finding a certain soil within a polygon. The number of similar and dissimilar pedons within a map unit and multivariate zone was determined, and probabilities of success (p), error (E), 80% confidence intervals, and predicted number of observations [$E(n)$] needed to classify each unit were determined.

RESULTS AND DISCUSSION

Electrical Conductivity and Terrain Attributes Within Soil Survey Map Units

Macon Site

The mean field $EC_{a(0–30\ cm)}$ and $EC_{a(0–90\ cm)}$ were 5.51 and 6.53 mS m^{-1}, respectively. Shallow EC_a increased with increasing slope, and the highest mean $EC_{a(0–30\ cm)}$ was observed in the highest slope class (Table 3). Higher $EC_{a(0–30\ cm)}$ in steeper slope classes is due to a higher degree of historical erosion exposing clayier sub-surface horizons (Tomer and James, 2004), and positive correlation between EC_a and eroded areas has been found by other authors (Johnson et al., 2001; Johnson et al., 2003).

In general, map units containing Typic Paleudults had lower EC values (Table 3). Typic Paleudults reside at the highest elevation with a relatively low flow accumulation and CTI, whereas Aquic Paleudults reside at the lowest elevations and have the highest flow accumulation and CTI (Table 3). Large contributing areas and concave curvature with a corresponding high CTI result in more poorly drained soils (Tomer and James, 2004); Aquic Paleudults typify these conditions.

Dale Site

In Year 1, mean $EC_{a(0–30\ cm)}$ was 0.95 mS m^{-1}, and mean $EC_{a(0–90\ cm)}$ was 1.19 mS m^{-1}, whereas in Year 2, mean $EC_{a(0–30\ cm)}$ was 1.98 mS m^{-1}, and mean $EC_{a(0–90\ cm)}$ was 2.36 mS m^{-1}. The increase between years is due to greater soil moisture when readings were taken in Year 2. Soils at this site are sandy and well drained, thus resulting in lower overall EC_a values compared with the Macon site. Negative correlation has been observed between EC_a and sand content in previous research (Mueller et al., 2003; Moral et al., 2010), and low soil-water content (associated with sandier soils) often results in lower EC_a values (Sheets and Hendrickx, 1995; Kravchenko et al., 2002).

Shallow conductivity generally increased with increasing slope (Table 3). Map units containing soils in fine-particle-size families had the highest $EC_{a(0–30\ cm)}$, and the lowest $EC_{a(0–30\ cm)}$ was found in coarse-loamy map units (Table 3). The $EC_{a(0–90\ cm)}$ data better coincide with the particle size control section and taxonomic placement, and similar to the shallow depth, map units with soils mostly in fine-particle-size family units had the highest $EC_{a(0–90\ cm)}$. Similarly, the lowest $EC_{a(0–90\ cm)}$ values were recorded in coarse-loamy map units, which have a lower sub-soil clay content. These data are consistent with numerous studies relating EC_a with soil texture (Williams and Hoey, 1987; Mueller et al., 2003; Shaw and Mask, 2003; Sudduth et al., 2003; Weaver et al., 2004; Moral et al., 2010).

The EC increased with depth within fine and fine-loamy pedons; however, EC_a values in coarse-loamy map units decreased slightly with depth in both years. Within fine map units, the EC increased with depth by 0.38 and 0.72 mS m^{-1} for Years 1 and 2, respectively, whereas it decreased with depth within coarse-loamy map units by 0.12 and 0.29 mS m^{-1} for Years 1 and 2, respectively (Table 3). These data indicate that the relative comparison of shallow and deep EC can possibly be used to help differentiate sub-soil soil texture in similar settings and possibly facilitate taxonomic placement and survey of soils.

Relationships Between Electrical Conductivity and Soil and Terrain Attributes

Correlation between EC_a and surface texture (0–30 cm) was analyzed for both research sites (Table 4). Similar to past research, positive correlation was found between clay content and shallow EC_a at the Macon site (Williams and Hoey, 1987; Johnson et al., 2001; Johnson et al., 2003; Mueller et al., 2003; Sudduth et al., 2003). A positive correlation between EC_a and MDS, and clay content and MDS, was also found. Multiple linear regression ($p < 0.0001$) indicated that 62% of the surface clay content variability could be explained with EC data. For the Dale site, EC was also positively correlated with clay content and negatively correlated with sand content (Table 4). Multiple linear regression ($p = 0.0003$) indicated that 61% of the surface clay content variability could be explained with EC data. Positive correlation between conductivity and elevation was also found and is due to the fact that the soils in fine-particle-size families mostly reside at higher elevations at the Dale site.

Comparison of Conventional Soil Survey With Multivariate Zone Approach

Macon Site

Multivariate zones at the Macon site developed by the clustering technique were named for the dominant soil observed within the zone (Tables 5). Multivariate Zones 1 and 2 (a and b),

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TABLE 3. Averages of Electrical Conductivity and Terrain Attributes (With S.D. in Parentheses) Within Conventional Soil Survey Map Units and Slope Classes for Macon County and Dale County, Alabama, Sites[†]

Map Unit	First Acquisition		Second Acquisition		Elevation	Prof Curve	Plan Curve	FA	CTI
	EC a(0–30 cm)	EC a(0–90 cm)	EC a(0–30 cm)	EC a(0–90 cm)					
	mS m^{-1}				m				
Macon County, Alabama, Site									
SuA, Summerton sandy loam, 0%–2% slopes	5.05 (0.62)	6.26 (0.88)	ND	ND	70.06 (0.27)	−0.03 (0.03)	0.01 (0.02)	2.37 (2.33)	1.54 (2.56)
NsA, Noboco (tax)-Summerton complex, sandy loam, 0%–2% slopes	5.17 (0.94)	5.95 (1.20)	ND	ND	69.88 (0.19)	−0.03 (0.04)	0.01 (0.02)	1.91 (3.21)	−0.09 (2.83)
NoC, Noboco (tax) sandy clay loam, 4%–6% slopes	7.24 (1.55)	6.93 (0.71)	ND	ND	69.27 (0.47)	−0.01 (0.06)	−0.02 (0.02)	5.52 (4.27)	2.97 (0.69)
NoB, Noboco (tax) sandy clay loam, 2%–4% slopes	6.76 (1.49)	7.53 (1.23)	ND	ND	69.44 (0.36)	−0.02 (0.04)	−0.01 (0.01)	6.34 (4.04)	3.41 (0.92)
NoA, Noboco (tax) sandy loam, 0%–2% slopes	5.44 (0.81)	6.51 (1.04)	ND	ND	69.95 (0.07)	−0.03 (0.04)	0.00 (0.02)	1.62 (2.36)	−0.15 (3.28)
DnB, Duplin-Noboco (tax) complex, loam, 2%–4% slopes	5.69 (1.07)	6.43 (1.43)	ND	ND	69.52 (0.20)	0.00 (0.04)	−0.02 (0.02)	10.99 (13.62)	3.56 (2.00)
DoB, Duplin-Noboco (tax) complex, sandy clay loam, 2%–4% slopes	7.32 (1.36)	8.13 (0.82)	ND	ND	69.16 (0.31)	−0.02 (0.04)	−0.01 (0.02)	2.94 (2.41)	2.58 (1.49)
DuA, Duplin sandy loam, 0%–2% slopes	5.20 (1.82)	6.29 (1.62)	ND	ND	68.57 (0.30)	0.04 (0.04)	−0.03 (0.02)	10.87 (9.52)	4.43 (0.60)
DpA, Duplin loam, 0%–2% slopes	4.71 (0.78)	5.82 (1.26)	ND	ND	68.11 (0.14)	0.05 (0.02)	−0.03 (0.02)	50.84 (49.17)	6.12 (0.99)
0%–2% slope	4.97 (0.93)	6.22 (1.15)	ND	ND	NA	NA	NA	NA	NA
2%–4% slope	6.52 (1.54)	7.31 (1.46)	ND	ND	NA	NA	NA	NA	NA
4%–6% slope	7.44 (1.31)	6.84 (0.62)	ND	ND	NA	NA	NA	NA	NA
Dale County, Alabama, Site									
FaB, Faceville sandy loam, 2%–6% slopes	1.28 (0.52)	1.66 (0.47)	2.61 (0.73)	3.33 (0.96)	103.70 (0.85)	−0.05 (0.05)	0.02 (0.07)	0.82 (0.93)	0.46 (2.43)
FaC, Faceville sandy loam, 6%–12% slopes	1.10 (0.62)	1.40 (0.83)	2.17 (0.81)	2.55 (1.20)	100.01 (2.61)	0.01 (0.07)	−0.04 (0.05)	6.60 (10.52)	2.55 (1.03)
OaB, Orangeburg loamy sand, 2%–6% slopes	0.93 (0.45)	1.24 (0.74)	1.98 (0.78)	2.50 (1.40)	101.30 (2.91)	−0.04 (0.06)	0.03 (0.06)	1.40 (2.42)	−0.32 (2.69)
OaC, Orangeburg loamy sand, 6%–12% slopes	0.78 (0.29)	0.87 (0.24)	1.63 (0.28)	1.88 (0.42)	95.93 (1.20)	0.06 (0.10)	0.02 (0.05)	4.91 (7.88)	1.34 (1.87)
OrA, Orangeburg sandy loam, 0%–2% slopes	0.88 (0.18)	1.46 (0.31)	2.08 (0.39)	3.59 (0.64)	105.47 (0.10)	−0.05 (0.05)	0.01 (0.04)	0.03 (0.10)	−3.09 (2.15)
BeB, Benevolence loamy sand, 2%–6% slopes	0.74 (0.26)	0.62 (0.19)	1.52 (0.35)	1.23 (0.30)	98.08 (1.49)	0.00 (0.05)	−0.02 (0.06)	6.98 (5.88)	2.15 (2.35)
0%–2% slope	0.89 (0.22)	1.50 (0.38)	1.97 (0.31)	3.53 (0.61)	NA	NA	NA	NA	NA
2%–6% slope	0.91 (0.46)	1.14 (0.73)	1.93 (0.77)	2.28 (1.39)	NA	NA	NA	NA	NA
6%–12% slope	1.01 (0.60)	1.29 (0.77)	2.07 (0.76)	2.43 (1.09)	NA	NA	NA	NA	NA

[†]$EC_{a(0–30\ cm)}$: EC_a at 0–30 cm; $EC_{a(0–90\ cm)}$: EC_a at 0–90 cm; Prof Curve: profile curvature; Plan Curve: planimetric curvature; FA: flow accumulation; CTI: compound topographic index; ND: not determined; NA: not applicable.

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TABLE 4. Pearson Linear Correlation Coefficients ($p \leq 0.05$) Between Electrical Conductivity, Surface (0–30 cm) Soil Texture, and Terrain Attributes for Macon County, Alabama, and Dale County, Alabama, Research Sites†

	1st Acquisition		2nd Acquisition		Sand	Silt	Clay			Prof	Plan		
	$EC_{a(0–30\ cm)}$	$EC_{a(0–90\ cm)}$	$EC_{a(0–30\ cm)}$	$EC_{a(0–90\ cm)}$	(%)	(%)	(%)	Elevation	MDS	Curve	Curve	FA	CTI
$EC_{a(0–30\ cm)}$ (1st)	1	0.73	NA	NA	−0.36	NS	0.64	−0.16	0.45	NS	−0.05	−0.04	NS
$EC_{a(0–90\ cm)}$ (1st)	*0.82*	1	NA	NA	NS	NS	NS	−0.05	0.39	−0.10	NS	−0.11	NS
$EC_{a(0–30\ cm)}$ (2nd)	*0.77*	*0.85*	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
$EC_{a(0–90\ cm)}$ (2nd)	*0.65*	*0.91*	*0.87*	1	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sand (%)	*−0.88*	*−0.89*	*−0.82*	*−0.79*	1	−0.60	−0.61	ND	NS	ND	ND	ND	ND
Silt (%)	*NS*	*0.51*	*NS*	*0.49*	*−0.49*	1	−0.27	ND	−0.31	ND	ND	ND	ND
Clay (%)	*0.87*	*0.85*	*0.81*	*0.75*	*−0.98*	*NS*	1	ND	0.49	ND	ND	ND	ND
Elevation	*0.43*	*0.68*	*0.57*	*0.73*	*ND*	*ND*	*ND*	1	−0.17	−0.37	0.21	−0.28	−0.39
MDS	*−0.20*	*−0.12*	*−0.13*	*−0.12*	*NS*	*NS*	*NS*	*−0.14*	1	−0.20	0.05	−0.11	0.07
Prof curve	*0.21*	*0.07*	*0.10*	*NS*	*ND*	*ND*	*ND*	*−0.12*	*−0.47*	1	−0.45	0.14	0.47
Plan curve	*−0.11*	*−0.04*	*−0.06*	*NS*	*ND*	*ND*	*ND*	*0.05*	*0.23*	*−0.49*	1	−0.23	−0.58
FA	*NS*	*−0.09*	*−0.06*	*−0.12*	*ND*	*ND*	*ND*	*−0.17*	*−0.17*	*0.21*	*−0.23*	1	0.33
CTI	*0.11*	*NS*	*0.05*	*NS*	*ND*	*ND*	*ND*	*−0.10*	*−0.24*	*0.48*	*−0.58*	*0.47*	1

Dale County, Alabama, correlation coefficients are in italics.

†$EC_{a(0–30\ cm)}$: EC_a at 0–30 cm; $EC_{a(0–90\ cm)}$: EC_a at 0–90 cm; MDS: maximum downhill slope; Prof Curve: profile curvature; Plan Curve: planimetric curvature; FA: flow accumulation; CTI: compound topographic index; NS: not significant at $P \leq 0.05$; ND: not determined; NA: not applicable.

with relatively high flow accumulation and CTI, consisted mostly of Oxyaquic and Aquic Paleudults. Multivariate Zone 3, residing at a low elevation, consisted mostly of Oxyaquic Paleudults. Multivariate Zone 4, residing at relatively high elevations and having the lowest EC_a values, flow accumulation, and CTI, consisted mostly of Typic and Oxyaquic Paleudults. Multivariate Zone 5 (a and b), with the highest EC_a, flow accumulation, and CTI, and low elevation, consisted mostly of Aquic Paleudults. Lastly, multivariate Zone 6 consisted mostly of Oxyaquic Paleudults.

Using our rigid criteria for similar-dissimilar assessment (discussed in Materials and Methods), the probabilities of success (p), or the probability of observing the named soil within a multivariate zone, ranged between 29% and 67% at the Macon site. Averaged for all units, the probability of success for the multivariate zone approach was 50%, whereas the probability of success for the conventional survey approach was 55% (Table 5). Overall means of the estimated errors for the probability of success were generally low: ~22% to 23% for both approaches. At the 80% confidence interval, 28% to 72% of the pedons are the same as the named map unit for the multivariate zone approach, and 33% to 77% of the pedons are the same as the named map unit for the conventional survey approach. For both approaches, nine soil observations within each unit are needed to estimate p within 20%.

Dale Site

At the Dale site, multivariate Zone 1, residing at low elevations and having high CTI, consisted mostly of coarse-loamy soils (Table 6). Multivariate Zone 2, residing at intermediate elevations and having low EC_a and high flow accumulation, consisted mostly of fine-loamy soils. Multivariate Zone 3, residing at high elevations with high EC_a and low flow accumulation and CTI, consisted mostly of fine and fine-loamy soils.

Few patterns are similar between the conventional and multivariate zone approaches at the Dale site (i.e., compare Fig. 2 and Fig. 4), with the exception of fine-loamy map units with 0% to 2% and 6% to 12% slope classes. One significant difference between approaches at the Dale site is that the majority of the conventional survey area (6.1 ha) is within fine-loamy map units, whereas the multivariate zone approach has more coarse-loamy map units throughout the site (3.4 ha).

The overall mean probability of success was high for the Dale (compared with the Macon) site: 79% for the conventional approach and 76% for the multivariate zone approach (Table 6). Overall means of the estimated errors for the probability of success were low, from 8% for the multivariate zone approach to 15% for the conventional approach. The multivariate zone approach had relatively lower probabilities of success for the larger multivariate zones but was better than the conventional approach for smaller zones. Averaged overall, at the 80% confidence interval, 67% to 84% of the pedons are the same as the named map unit for the multivariate zone approach, and 64% to 94% of the pedons are the same as the named map unit for the conventional approach. The number of observations needed to estimate probabilities of success within 20% for each map unit and multivariate zone was low for both approaches, although the number of observations needed for the conventional approach (n = 6) was higher than that of the multivariate zone approach (n = 5) (Table 6).

At both sites, the multivariate zone approach had a slightly lower probability of success (3% and 5%) compared with the conventional approach, whereas estimated error associated with probabilities of success and numbers of observations needed was lower for the multivariate zone approach at one site (Dale). Although the maps are qualitatively different (visually), similar numbers of polygons were obtained for both sites for both techniques, suggesting a relatively equal "landscape efficiency" for the approaches.

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TABLE 5. Binomial Statistics Comparing the Conventional Soil Survey Approach to the Landscape Zone Approach for an Order 1 Soil Survey of a 9-ha Macon County, Alabama, Research Site

Zones	Name	*n*	*p*	*q*	*E*	80% CI‡	*E*(*n*)
1	DoB, Duplin-Noboco (tax) complex, sandy clay loam, 2%–4% slopes	10	0.5	0.5	0.2	$0.30 < P < 0.70$	10
2a	DuA, Duplin sandy loam, 0%–2% slopes	6	0.67	0.33	0.25	$0.42 < P < 0.91$	9
2b	GnB, Goldsboro-Noboco complex, sandy clay loam, 2%–4% slopes	7	0.29	0.71	0.22	$0.07 < P < 0.50$	8
3	Nba, Noboco (tax) loam, 0%–2% slopes	8	0.38	0.62	0.22	$0.16 < P < 0.59$	10
4	NsA, Noboco (tax) -Summerton complex, sandy loam, 0%–2% slopes	21	0.29	0.71	0.13	$0.16 < P < 0.41$	8
5a	DuA, Duplin sandy loam, 0%–2% slopes	3	0.67	0.33	0.35	$0.32 < P < 1$	9
5b	DuB, Duplin sandy clay loam, 2%–4% slopes	6	0.67	0.33	0.25	$0.42 < P < 0.91$	9
6	NoB, Noboco (tax) sandy clay loam, 2%–4% slopes	13	0.54	0.46	0.18	$0.36 < P < 0.72$	10
	Overall average	9	0.50	0.50	0.23	$0.28 < P < 0.72$	9
Survey	**Name**	***n***	***p***	***q***	***E***	**80% CI‡**	***E*(*n*)**
	SuA, Summerton sandy loam, 0%–2% slopes	11	0.64	0.36	0.19	$0.45 < P < 0.82$	9
	NoB, Noboco (tax) sandy clay loam, 2%–4% slopes	15	0.40	0.60	0.16	$0.24 < P < 0.56$	10
	NoC, Noboco (tax) sandy clay loam, 4%–6% slopes	8	0.63	0.38	0.22	$0.41 < P < 0.84$	10
	DuA, Duplin sandy loam, 0%–2% slopes	10	0.7	0.3	0.19	$0.51 < P < 0.89$	9
	DoB, Duplin-Noboco (tax) complex, sandy clay loam, 2%–4% slopes	6	0.5	0.5	0.26	$0.24 < P < 0.76$	10
	DpA, Duplin loam, 0%–2% slopes	4	0.75	0.25	0.28	$0.47 < P < 1$ 8	
	NoA, Noboco (tax) sandy loam, 0%–2% slopes	6	0.67	0.33	0.25	$0.42 < P < 0.91$	9
	DnB, Duplin-Noboco (tax) complex, loam, 2%–4% slopes	6	0.33	0.67	0.25	$0.09 < P < 0.58$	9
	NsA, Noboco (tax) -Summerton complex, sandy loam, 0%–2% slopes	9	0.33	0.67	0.20	$0.13 < P < 0.53$	9
	Overall average	8	0.55	0.45	0.22	$0.33 < P < 0.77$	9

Observations were interpreted to be similar if soils were the same taxa as named unit; dissimilar otherwise.

†*n*: sample size; *p*: probability of success (probability of observing same soil family as named unit); *q*: probability of failure; *E*: error; 80% CI: 80% confidence interval; *E*(*n*): expected sample size required.

‡$\alpha = 0.20$; $Z(\alpha / 2) = 1.28$.

TABLE 6. Binomial Statistics Comparing the Conventional Soil Survey Approach to the Landscape Zone Approach for an Order 1 Soil Survey of an 8-ha Dale County, Alabama, Research Site

Zones	Name	*n*	*p*	*q*	*E*	80% CI‡	*E*(*n*)
1a	BeB, Benevolence loamy sand, 2 to 6 percent slopes	21	0.43	0.57	0.14	$0.29 < P < 0.57$	10
1b	OaC, Orangeburg loamy sand, 6 to 12 percent slopes	13	0.62	0.38	0.17	$0.45 < P < 0.79$	10
2	BeBa, Benevolence sandy loam, 2 to 6 percent slopes	3	1	0	0	1	1
3a	OrA, Orangeburg sandy loam, 0%–2% slopes	4	1	0	0	1	1
3b	FoB, Faceville-Orangeburg complex, loamy sand, 2 to 6 percent slopes	12	0.5	0.5	0.18	$0.32 < P < 0.68$	10
3c	OaC, Orangeburg loamy sand, 6 to 12 percent slopes	4	1	0	0	1	1
	Overall average	10	0.76	0.24	0.08	$0.67 < P < 0.84$	5
Survey	**Name**	***n***	***p***	***q***	***E***	**80% CI‡**	***E*(*n*)**
	BeB, Benevolence loamy sand, 2 to 6 percent slopes	9	1	0	0	1	1
	FaB, Faceville sandy loam, 2 to 6 percent slopes	6	0.83	0.17	0.19	$0.64 < P < 0.92$	6
	OaC, Orangeburg loamy sand, 6 to 12 percent slopes	12	0.92	0.08	0.10	$0.82 < P < 1$	3
	OrA, Orangeburg sandy loam, 0%–2% slopes	6	0.83	0.17	0.19	$0.64 < P < 1$	6
	OaB, Orangeburg loamy sand, 2 to 6 percent slopes	17	0.59	0.41	0.15	$0.44 < P < 0.74$	10
	FaC, Faceville sandy loam, 6 to 12 percent slopes	7	0.57	0.43	0.24	$0.33 < P < 0.81$	10
	Overall average	10	0.79	0.21	0.15	$0.64 < P < 0.94$	6

Observations were interpreted to be similar if soils were the same taxa as named unit; dissimilar otherwise.

†*n*: sample size; *p*: probability of success (probability of observing same soil family as named unit); *q*: probability of failure; *E*: error; 80% CI: 80% confidence interval; *E*(*n*): expected sample size required.

‡$\alpha = 0.20$; $Z(\alpha / 2) = 1.28$.

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CONCLUSIONS

Significant correlation between EC_a signatures and surface texture was evident for these loamy to sandy soils of the Alabama Coastal Plain. Shallow EC_a differed between surface texture phases and thus may be used to facilitate soil map unit surface texture phase identification in this region. At the Dale site, EC increased with depth within fine and fine-loamy pedons mimicking clay increase, whereas EC_a values in coarse-loamy map units slightly decreased with depth. Thus, the relative comparison of shallow and deep EC_a may be used to differentiate subsoil texture in similar coastal plain soils. In summary, these results suggest that EC_a values can facilitate depiction of soil texture variability in these coastal plain landscapes.

Differences in EC_a and terrain attributes between multivariate zones were exhibited, suggesting that the multivariate clustering technique captured landscape and EC variability. Principal factor loadings indicate that EC and elevation explained the majority of the cumulative variability of the landscape features at these sites.

When the rigid similar-dissimilar rule for this exercise is considered, the GIS-based multivariate technique provided acceptable probabilities of success of observing the named soil within a map unit for this first-order survey application. However, probabilities of success using the conventional approach slightly exceeded those of the multivariate zone approach at both sites, although there were just very slight differences in metrics associated with accuracy. When viewed in total, the two approaches were similar in accuracy, although the actual survey maps are qualitatively (visually) different. Similar numbers of delineations were obtained for both sites for both techniques, suggesting a relatively equal "landscape efficiency" for the approaches.

In summary, an approach has been investigated whereby multivariate analyses were used to group landscape and EC variability before pedon observations for first-order soil survey development. This approach incorporates technologies that collect georeferenced soil and landscape data that provide high-resolution information regarding the soil continuum. The product of this GIS-based technique is used to guide first-order soil survey development. In reality, a multitude of combinations of these and related data could be investigated for this application. Thus, the study serves as an investigation of a conceptual approach rather than a rigid technique. Although the results of the two approaches were similar, the multivariate zone technique requires less knowledge of the local soil-landscape paradigm before survey development, but more knowledge of the technology and GIS-based clustering techniques.

ABBREVIATIONS

EC: electrical conductivity;
DEM: digital elevation model;
CTI: compound topographic index;
EC_a: apparent electrical conductivity;
CEC: cation exchange capacity;
MDS: maximum downhill slope.

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