Landscape Ecology **16:** 377–390, 2001.

Research Article

Detection of edaphic discontinuities with ground-penetrating radar and electromagnetic induction

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Received 7 April 1999; Revised 20 June 2000; Accepted 20 March 2001

Key words: apparent conductivity, argillic horizon, edaphic discontinuity, plant-soil relationships, soil, soil mapping, soil map unit boundaries, soil survey, spatial variation

Abstract

Quantification of edaphic properties which may regulate the spatial distribution of vegetation is often limited by the expense and labor associated with collecting and analyzing soil samples. Here we evaluate the utility of two technologies, ground-penetrating radar (GPR) and electromagnetic induction (EMI), for rapid, extensive and non-destructive mapping of diagnostic subsurface features and soil series map unit boundaries.

Strong reflectance from fine-textured, near-surface soils obscured radar signal reflectance from deeper horizons at our field test site in the Rio Grande Plains of southern Texas, USA. As a result, ground-penetrating radar did not delineate known edaphic contrasts along catena gradients. In contrast, EMI consistently distinguished boundaries of soil map units. In several instances, gradients or contrasting inclusions within map units were also identified. In addition, the location and boundary of calcic or cambic-horizon inclusions embedded within a laterally co-extensive and well-developed argillic horizon were consistently predicted. Correlations between EMI assessments of apparent conductivity (ECa) and soil properties such as CEC, pH, particle size distribution and extractable bases were low (i.e., explained <6% of the variance), or non-significant. As a result, EMI has a high prospecting utility, but cannot necessarily be used to explain the basis for edaphic contrasts.

Results suggest EMI can be a cost-effective tool for soil survey and exploration applications in plant ecology. As such, it is potentially useful for rapidly locating and mapping subsurface discontinuities, thereby reducing the number of ground truth soil samples needed for accurate mapping of soil map unit boundaries. An application, addressing hypotheses proposed to explain the role of edaphic heterogeneity in regulating woody plant distribution in a savanna parkland landscape, is presented.

Introduction

Spatial variability in subsoil properties (depth, structure, texture, horizonation, chemistry) is a potentially important control over plant composition, distribution and production. However, quantification of the pattern and extent of spatial variation in edaphic properties is often limited by the availability of expertise and the expense and labor associated with obtaining and analyzing soil samples. Two technologies with potential for rapid, extensive and non-destructive surveys of ecologically relevant subsurface properties of soils are ground-penetrating radar (GPR) and electromagnetic induction (EMI).

GPR has been used by soil scientists to determine the presence, depth, extent and lateral variation of soil horizons and properties (Collins and Doolittle 1987; Mokma et al. 1990; Shih and Doolittle 1984; Truman et al. 1988). The technique has been most effective as a diagnostic tool where soils were coarse-textured with low electrical conductivity and least effective where soils were fine-textured with high electrical conductivity (Doolittle 1987). Electromagnetic induction has been widely used by agronomists to estimate soil salinity (de Jong et al. 1979; Rhoades and Corwin 1981; Williams and Baker 1982; Wollenhaupt et al. 1986; Williams and Hoey 1987; Corwin and Rhoades 1990; Rhoades and Corwin 1990) and moisture content (Kachanoski et al. 1988), to map sodium-affected soils (Ammons et al. 1989; Hendrickx et al. 1992; Cannon et al. 1994; Nettleton et al. 1994) and regional differences in soil mineralogy (Doolittle et al. 1995), to determine depths to claypans (Doolittle et al. 1994) and to indicate textural discontinuities within profiles (Williams et al. 1990; Wollenhaupt et al. 1986). The technique has also been used in mapping of geologic strata (Zalasiewicz et al. 1965; Brus et al. 1992), groundwater recharge (Cook et al. 1992; McNeill 1991) and groundwater contamination (Greenhouse and Slaine 1983). Despite the potential utility of these non-destructive, portable technologies for rapidly and extensively quantifying sub-surface soil properties important to plant production and distribution, there have been few ecological applications.

The occurrence of distinctive patterns of vegetation on landscapes at the La Copita Research Area in the Rio Grande Plains of southern Texas, USA provided the impetus to evaluate the utility of using GPR and EMI to quantify plant-soil relationships. Uplands at this site consist of sandy loam surface soils (0–40 cm) underlain by a well-developed, fine-loamy argillic horizon (40–100 cm depth). The argillic horizon is laterally extensive across uplands, but contains inclusions of sandy loam subsoils (cambic or calcic horizons) that reveal no evidence of argillic horizon formation (Loomis 1989; Stokes 1999). These contrasts in soil texture have a significant influence on vegetation patterns. The non-argillic inclusions typically support well-developed groves dominated by large honey mesquite trees (*Prosopis glandulosa* var. *glandulosa* Torr.), whereas vegetation on soils with argillic horizons are characterized by small, discrete shrub clusters interspersed in a grassy matrix (Archer 1995). Understory shrubs common to both groves and discrete shrub clusters include *Zanthoxylum fagara* (L.) and *Diospyros texana* (Scheele.), broad-leafed evergreens; deciduous *Celits pallida* (Torr.) and *Condalia hookeri* (M.C. Johnst.); *Ziziphus obtusifolia* (T.& C.), stem photosynthetic and drought deciduous; and *Berberis trigoliolata* (Moric.), a schlerophyllous evergreen. Relative to woody plants in discrete clusters, those in groves are larger and exhibit greater growth rates (Archer 1995), greater seed production (El Youssoufi 1992) and lower root/shoot ratios (Watts 1993).

It is not clear whether the non-argillic inclusions represent isolated patches where an argillic horizon has been obliterated subsequent to the establishment of woody plants (e.g., by faunal mixing) or whether woody plants are differentially exploiting portions of the landscape where the argillic horizon never formed. Available data from micro-fabric reconstruction support the latter hypothesis (Loomis 1989). If subsurface discontinuities in the argillic horizon are pre-existing conditions, portions of the landscape may still exist where, by chance, groves of woody plants have not yet developed. Geophysical tools (e.g., GPR or EMI) that differentiate cambic and argillic horizons could therefore provide insights into the pedogenic origins of these upland soils and identify areas where vegetation change (e.g., future establishment of woody plants and the development of groves) would be most probable. In addition, GPR and EMI would have potential as cost-effective tools for soil survey, reconnaissance and exploration applications if they could be used to strategically locate representative or unique edaphic patches within landscapes, thereby guiding the spatial arrangement of sampling and reducing the number of soil samples needed for accurate mapping. Here we examine the potential utility of GPR and EMI for assessing the spatial distribution of non-argillic subsoils and to assess the location of soil series map unit boundaries.

Methods

Study site

Fieldwork was conducted on the Texas A&M University La Copita Research Area (LCRA), approximately 65 km west of Corpus Christi, Texas, USA in Jim Wells county (27°40′ N, 98°12′ W). Elevation at the LCRA ranges from 75 to 90 m and topography is gently undulating with slopes $<3\%$. The climate of the region is subtropical with mild winters and hot summers. Average annual temperature is 22.4 °C. Mean annual rainfall (720 mm) is bimodally distributed with maxima in May and September (USDA 1979). Series descriptions of soils on the study site are summarized in Table 1. Additional summaries of soils, vegetation and climate of the La Copita can be found in Scifres and Koerth (1987) and Archer (1995).

Table 1. Mapping unit legend and classification of soils on the study site (from USDA 1979).

Topographic position	Map unit	Series name	Classification	Avg. depth to B horizon (cm)
Uplands	6, 6A	Czar fine sandy loam, 1 to 3% slopes	Fine-loamy, mixed, superactive, hyperthermic Pachic Argiustolls	33
	19	Locoste-Olmos association, gently undulating	Locoste=Loamy, mixed, superactive, hyperthermic shallow Petrocalic Paleustalfs; Olmos=Loamy-skeletal, carbonatic, hyperthermic, shallow Petrocalcic Calciustolls	18–23
	23	Miguel fine sandy loam, 1 to 3% slopes	Fine, mixed, superactive, hyperthermic Typic Paleustalfs	25
	33	Pernitas fine sandy loam, 1 to 3% slopes	Fine-loamy, mixed, superactive, hyperthermic Typic Argiustolls	28
	40, 41	Pharr fine sandy loam, 1 to 3% slopes	Fine-loamy, mixed, superactive, hyperthermic Typic Argiustolls	38
	42A	Pharr sandy clay loam, 0 to 1% slopes	Fine-loamy, mixed, superactive, hyperthermic Typic Argiustolls	38
	46, 47	Runge fine sandy loam 0 to 1% slopes	fine-loamy, mixed, superactive, hyperthermic Typic Argiustolls	36
	49	Runge sandy clay loam, 0 to 1% slopes	Fine-loamy, mixed, superactive, hyperthermic Typic Argiustolls	36
Drainages	3	Clareville loam, 0 to 1% slopes	Fine, smectitic, hyperthermic Vertic	28
	14	Edroy clay, depressional	Fine, mixed, superactive, hyperthermic Pachic Augiustolls Haplaquolls	46
	27	Opelika fine sandy loam	Fine-loamy, mixed, superactive, hyperthermic Mollic Albaqualfs	10

EMI and GPR instrumentation

The ground penetrating radar (GPR) unit was a Subsurface Interface Radar [SIR] System 8 with a 120 MHz center frequency antenna (Model 3110; Geophysical Survey Systems, Inc.). See Doolittle (1987) and Daniels et al. (1988) for details on use and operation. The system was powered by a 12-VDC battery. Radar surveys were conducted by towing the antenna along flagged (3 m intervals) transect lines at a constant speed of about 1 km h^{-1}. As the antenna passed each flag along the transect, a notation was made on the radar output.

The electromagnetic induction meters used in the study were the EM38 and EM31 (Geonics Limited). Principles of operation have been described by McNeill (1980, 1986). These meters are lightweight, portable and can be operated by a single person. For each meter, lateral resolution is approximately equal to the intercoil spacing. The EM38 meter has a fixed intercoil spacing of about 1 m and operates at a frequency of 13.3 kHz. It has a theoretical observation depth of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (McNeill 1986). The EM31 meter has a fixed intercoil spacing of 3.7 m and operates at a frequency of 9.8 kHz. The EM31 has a theoretical observation depth of about 3 and 6 m in the horizontal and vertical dipole orientations, respectively (NcNeill 1980). Instrument outputs of apparent electrical conductivity (ECa) are expressed millisiemens per meter [mS m^{-1}].

Delineation of soil map units with EMI

Appropriateness of EMI for delineating boundaries between cartographic soil units was assessed along two transects in December 1991. A soil map (scale 1:4000) specifically developed for the La Capita Research Area (Guckian 1987) was used as a benchmark. This map was developed from field samples and aerial photography using standard USDA/Natural Resources Conservation Service (formerly Soil Conservation Service) protocol. Apparent electrical conductivity was recorded along the 330 m and 950 m transects at 30 m intervals. Two additional transects (1440 m and 1000 m) were sampled with the EM31 meter at 20 m intervals in October, 1992. The EM38 meter was not used in 1992 because data from the 1991 transects (Figure 2) suggested that the EM31 meter was more useful in detecting differences in soil properties that coincided with known map-unit boundaries. EMI values for each soil series were regressed

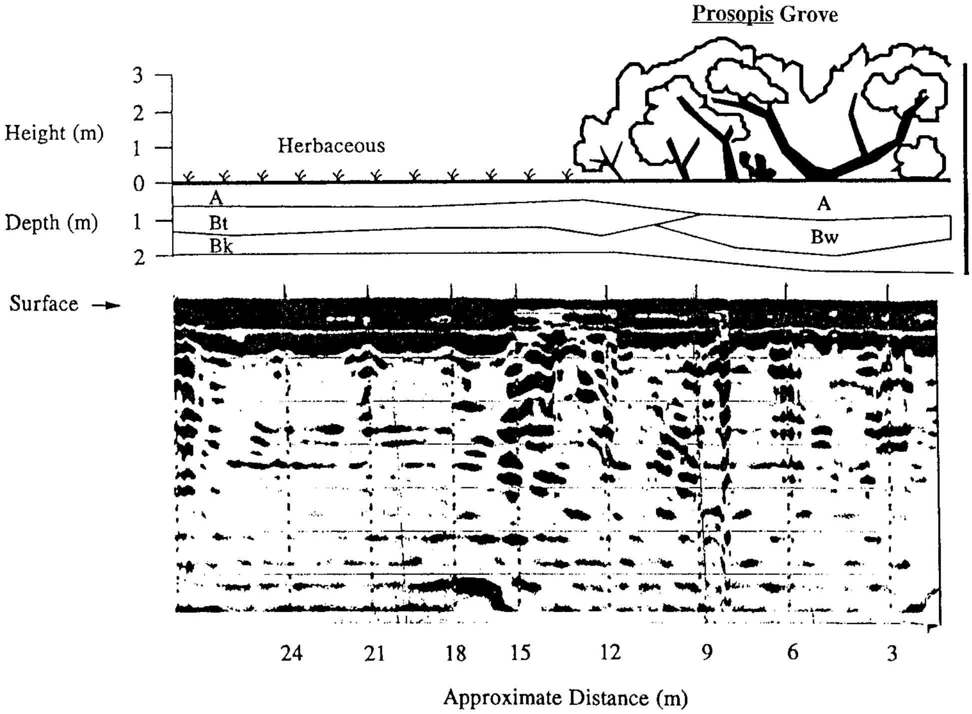

Figure 1. Ground-penetrating radar signature of a *Prosopis* grove and adjacent herbaceous zone. The presence/absence of well-developed argillic (Bt) horizons mapped along such transects (upper panel) could not be detected in the radar signal because of strong reflections from the soil surface (lower panel). As a result, no effort was made to quantify depth of radar penetration. Depth and horizonation of soils shown in the upper panel are from from Watts (1993).

against observation depth (EMI meters in the horizontal and vertical dipole positions) with a general linear model procedure for a polynomial design (SAS 1990).

Correlations between ECa and soil properties

Soil cores (2.5 cm diameter; 1–1.5 m in depth) were taken from EMI surveys on uplands in 1991 at seven points. The sampled points spanned the full range ECa readings in both the herbaceous matrix (argillic horizon present) and in *Prosopis* groves (argillic horizon absent). Soil cores were divided into subsamples based on genetic horizonation (Soil Survey Staff 1981) Subsamples were analyzed for CEC (NH_4OAc, pH 7), pH (water-saturated paste), particle-size distribution (pipette), $CaCO_3$ (manometric), extractable bases (calcium, magnesium, potassium, and sodium) and saturated-extract electrical conductivity (Soil Survey Staff 1984). Simple and multiple step-wise regression analyses (SAS 1990) were performed on horizon subsamples ($n = 37$) and on weighted averages for soil cores ($n = 7$) to explore empirical relationships between ECa and soil physical and chemical properties. Weighted averages were calculated by multiplying attribute values by the thickness of the horizon, summing the products, and then dividing the total by the total depth of the core. Soil parameter values were used as independent variables; ECa values obtained from EM38 measurements in horizontal and vertical dipole orientations were used as response variables. Because all soil samples were <1.5 m in depth, only EM38 readings were used in regression analysis.

Remote sensing of non-argillic inclusions

The ground-penetrating radar unit was manually pulled along 25–30 m transects extending from the interior of three upland groves on suspected cambic (non-argillic) inclusions and into adjacent herbaceous zones presumed to have soils with well-developed argillic horizons. Trenches were then excavated along transects to a depth of 2 m with a backhoe and soil horizons were mapped and described (Watts 1993).

The sensitivity of EMI to cambic-horizon inclusions was tested on replicated ($n = 2$) uplands in October, 1992. Grids (54 points at 5 m intervals) were positioned such that about one-half of the sample points were within the area occupied by woody vegeta-

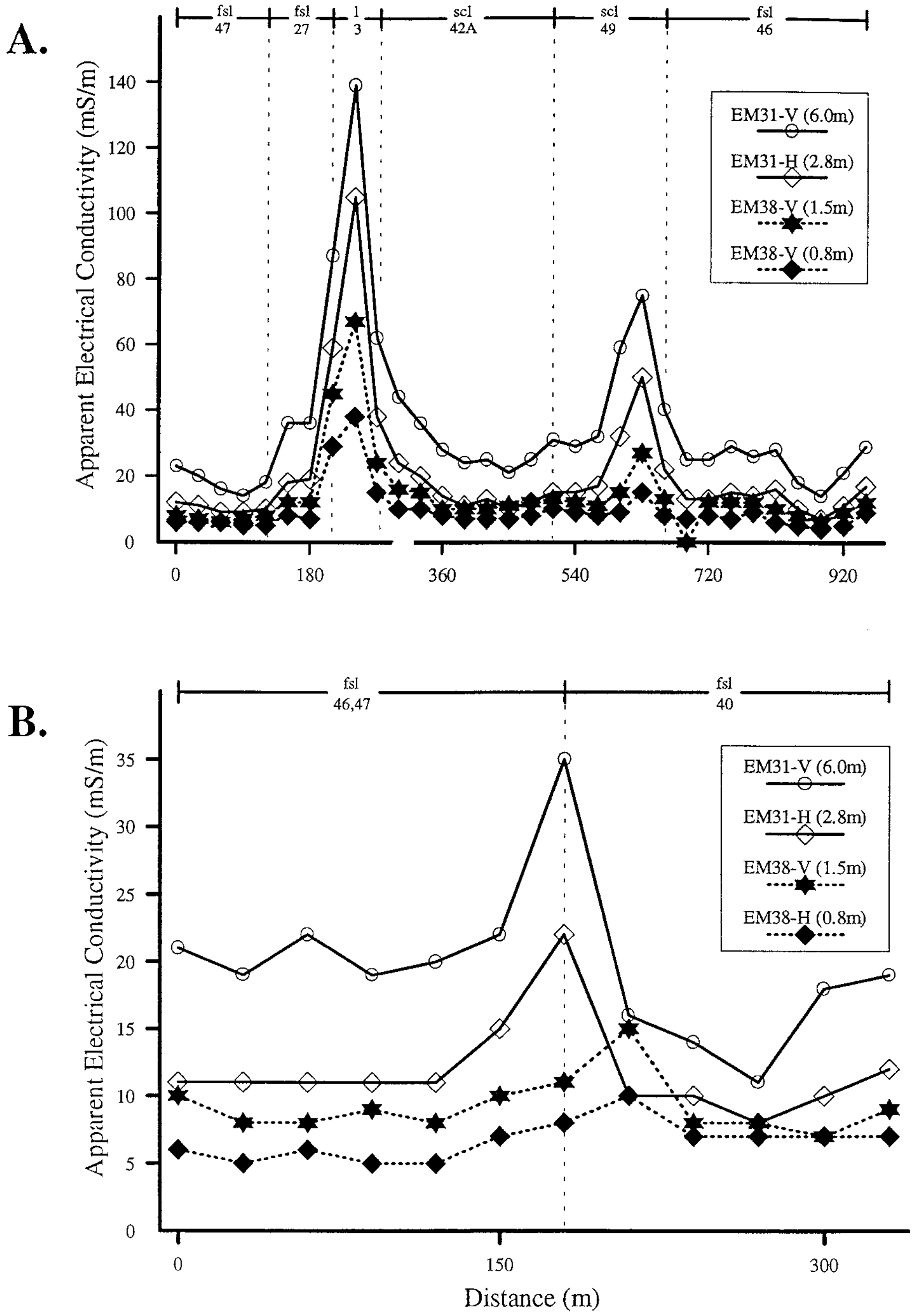

Figure 2. Apparent electrical conductivity in millisiemens per meter (ECa, mS m^{-1}) determined by two EMI meters (EM31 and EM38) in horizontal (H) and vertical (V) modes. Readings were taken at 30 m intervals along two transects (panels A and B) in 1991. Numbered dividers at the top of each graph indicate location of soil map unit boundaries as determined by independent field surveys (Guckian 1987). See Table 1 for elaboration of map unit numerical and soil texture codes.

tion associated with suspected cambic inclusions; the remaining points were in the adjacent herbaceous zone where the argillic horizon was presumably present and well-developed. After obtaining ECa readings at each grid point, soil cores (2.5 cm diam.; 0.6 m depth) were collected to confirm the presence/absence of an argillic horizon. Texture was estimated at depths representative of A and B horizons (15 and 55 cm [Loomis 1989]) using the field method of Brady (1984) and Thien (1979). Argillic horizons were scored as present if clay content increased between depths of 15 to 55 cm and visible clay films were observed on ped surfaces (Soil Survey Staff 1981). Logistic regression (Gujarati 1992; Hosmer and Lemesshow 1988) was used to analyze the relationship between apparent conductivity and the presence/absence of an argillic horizon using SAS/STAT (SAS 1990).

Logistic regression results were converted into probability curves using the following equations:

$$\mathrm{logit}(p) = b_0 + b_1(\text{EMI Value}), \tag{1}$$

$$p = \mathrm{e}^{\mathrm{logit}(p)}/(1 + \mathrm{e}^{\mathrm{logit}(p)}), \tag{2}$$

where p was the probability that an argillic horizon was absent at the point of EMI measurement.

After determination of probability curves, the EM38 was used to prospect for non-argillic inclusions on portions of three uplands typical of the La Coptia landscape dominated by herbaceous vegetation and small shrub clusters (i.e., non-grove sites). A 60 × 90 m grid was systematically positioned in the herbaceous areas within each at the three uplands and ECa was recorded at 5 m intervals along N–S and E–W transects. From these data, contour plots were generated (Surfer, Golden Software, Inc.). In addition, the size and shape of the non-argillic inclusion was confirmed by field sampling as described in the previous paragraph. These non-argillic inclusions were then georeferenced and their location delineated on sequential (1941, 1955, 1969, 1983, 1990) black and white aerial photographs (ca. 1:20 000) to quantify patch-specific changes in woody plant cover with time.

Results and discussion

Ground-penetrating radar

GPR has been effective for locating and mapping ortstein layers or argillic horizons in coarse-textured soils (Mokma et al. 1990; Truman et al. 1988) and in soils where the dominant clay mineral was kaolinite (Doolittle 1987). In finer-textured soils containing vermiculitic or smectitic clays (e.g., the La Copita study site; Loomis 1989), GPR has been less effective, as its observation depth is often <50 cm and in some cases <15 cm (Doolittle 1987).

The dominance of 2:1 expanding lattice clays of soils at the La Copita site (Loomis 1989) appeared to severely restrict the observation depth of ground-penetrating radar. In upland landscapes that consisted of Pharr, Runge and Miguel soil series (Table 1), we anticipated that the profiling depth of the 120 MHz antenna would be limited to the upper boundary of the subsoil. However, signals from shallow (ca. 40–50 cm) argillic horizons were masked by strong reflections nearer the soil surface. As a result, GPR could not differentiate cambic from argillic horizons (Figure 1). Because of the limited depth of observation and strong interference from near-surface soils, GPR does not appear to be useful for surveying and differentiating soil horizons and geologic sediments in this portion of the Rio Grande Plains.

EMI: correlations between ECa and soil properties

Correlations between ECa and soil properties (CEC, pH, particle-size distribution, $CaCO_3$, extractable bases and saturated-extract electrical conductivity) were low (explained $< 6\%$ of the variance) or non-significant ($P \geq 0.12$). A significant ($P < 0.03$) positive relationship between apparent conductivity obtained with the EM38 meter in the vertical dipole mode and saturated extract electrical conductivity (ECe) was found. The $r^2 = 0.25$ for the correlation between ECa and ECe was similar to that reported by Kachanoski et al. (1988). A low r^2, but significant ($P < 0.09$) negative relationship also emerged between ECa from the EM38 in the vertical dipole mode and exchangeable potassium. Although the reason for this relationship was unclear, it may have indicated higher concentrations of other salts that had displaced potassium ions. ECe and exchangeable K combined to explain about 32% of the variation in ECa. Relationships between weighted averages of other measured soil properties and ECa were non-significant.

Apparent conductivity significantly ($P < 0.01$) increased with depth for all but one soil (Tables 2 and 3), suggesting a net downward movement of soluble salts and a concentration of finer-textured materials in the lower part of soil profiles (Bresler et al. 1982; Corwin and Rhoades 1990). A significant interaction

Table 2. EMI estimates of mean (± SE) conductivity (mS m^{-1}) on upland and lowland soils of the Rio Grande Plains of southern Texas (fsl – fine, sandy loam; scl - sandy, clay loam; l – loam, c – clay). See Table 1 for descriptions of soil series; see Table 3 for statistical evaluations.

Landscape Position	Soil series	Landscape 1 (December, 1991)					Landscape 2 (October, 1992)		
		n	EM38-H (0.75 m)	EM38-V (1.5 m)	EM31-H (2.75 m)	EM31-V (6 m)	*n*	EM31-H (2.75 m)	EM31-V (6 m)
Drainages	Clareville l	2	26.5 (0.3)	45.5 (21.5)	71.5 (35.5)	100.5 (38.5)	46	52.7 (2.0)	72.8 (3.0)
	Opelika fsl	3	14.7 (7.2)	23.0 (11.0)	32.0 (13.5)	53.0 (17.0)	–	–	–
	Edroy c	–	–	–	–	–	2	100.0 (0.0)	116.0 (1.0)
Uplands	Runge fsl	21	6.2 (0.3)	9.1 (0.4)	12.3 (0.7)	22.1 (1.2)	39	35.7 (1.6)	44.7 (1.9)
	Runge scl	5	9.8 (1.3)	15.6 (2.9)	27.2 (6.4)	47.0 (8.7)	–	–	–
	Pharr fsl	5	7.6 (0.6)	9.4 (1.4)	10.0 (0.6)	15.6 (1.4)	–	–	–
	Pharr scl	8	8.7 (0.5)	12.1 (0.8)	14.9 (1.7)	29.3 (2.7)	–	–	–
	Czar fsl	–	–	–	–	–	29	40.7 (5.4)	51.7 (7.0)
	Pernitas fsl	–	–	–	–	–	2	23.0 (1.0)	23.0 (0.0)

Table 3. General Linear Model results for apparent electrical conductivity (ECa) measurements on two landscapes in the La Copita Research Area (see Table 2 for summary of means and SEs). Landscape one was sampled in 1991; landscape two was sampled in 1992. Results for main effects (SS = soil series, D = sample depths of EMI meters in the vertical and horizontal dipole modes) and their interaction (SS × D) are shown. A '–' denotes the model was linear and polynomial regression was not used.

Variable	Landscape 1 (December, 1991)	Landscape 2 (October, 1992)
SS	$P = 0.0001$	$P = 0.0001$
D	$P = 0.0001$	$P = 0.0001$
SS × D	$P = 0.001$	$P = 0.4342$
D^2	$P = 0.007$	–

($P < 0.05$) between EMI meters in vertical and horizontal modes and soils on Landscape 1 (Table 3) indicated that rates of increase in ECa with depth varied with soil series. For example, average EMI readings for Clareville soils on Landscape 1 increased by a factor of ca. 4 (from 26.5 mS m^{-1} at 0.75 m to 100.5 mS m^{-1} at 6 m). whereas EMI readings for Pharr soils increased by a factor of ca. 2 over the same depth (7.6 mS m^{-1} at 0.75 m; 15.6 mS m^{-1} at 6 m). For the soils encountered on Landscape 2, soil series × depth interactions were not significant. The one exception to the observed increase in ECa with depth occurred in the Pernitas map unit on Landscape 2 (Table 2). Though there were only two samples in this map unit, EMI readings may reflect an intrusion of the Lacoste–Olmos association which was in close proximity to this transect. Lacoste–Olmos soils are shallow to a petrocalcic horizon and would be expected to display low ECa and uniform conductivity profiles not characteristic of other soils in the study area.

EMI: delineation of soil map units

Apparent electrical conductivity values for transects were evaluated with respect to soil map units formulated by Guckian (1987). Soil delineations in intermittent drainages included Edroy clay, Clareville loam and Opelika fine sandy loam. These lowland map units had the highest average ECa values, whereas upland soils mapped as Pharr, Runge and Pernitas had the lowest average ECa readings (Table 2). Higher ECa readings for soils located in intermittent drainages were probably the result of their greater clay content (lowlands = >30%; uplands <20% [Boutton et al. 1998; Archer et al. 2000]).

Changes in ECa along transects typically coincided with changes in map units (Figures 2 and 3). The amplitude of EM3l distinctions between map units were greater than those obtained with the EM38 meter. In addition, instruments used in the vertical mode had greater signal amplitude at map boundaries than those used in the horizontal mode. Values of apparent conductivity within some map units were variable (e.g., Czar [map unit 6] in Figure 3a; Clareville [map unit 3] in Figure 3b), presumably indicative of heterogeneity within the map unit. Within the Czar map unit for example, areas of exposed caliche representa-

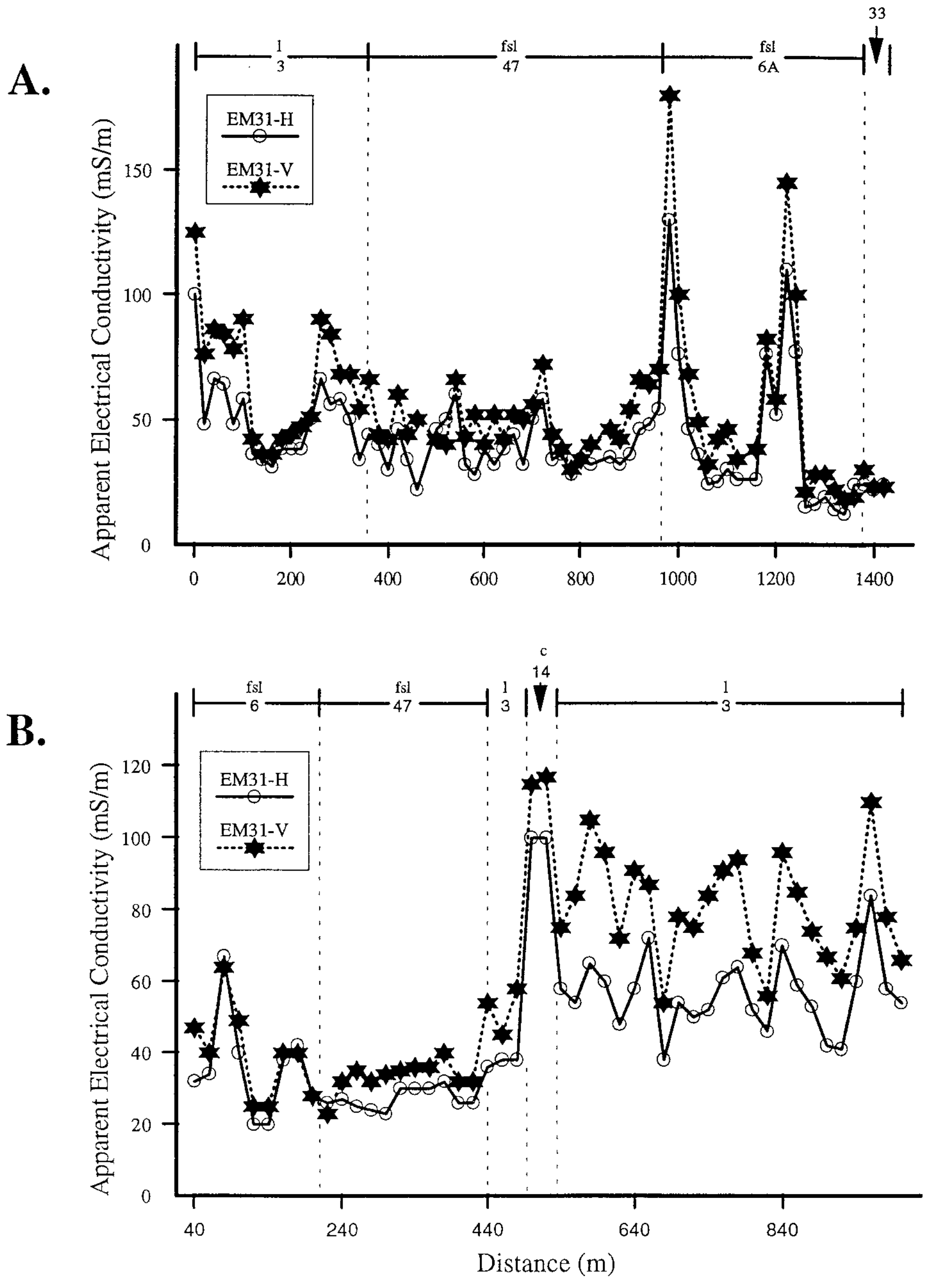

Figure 3. Apparent electrical conductivity (ECa, mS m^{-1}) determined by an EMI meter (EM31) in horizontal (H) and vertical (V) modes. Readings were taken at 20 m intervals along two transects (A and B) in 1992. Numbered dividers at the top of the graph indicate location of soil map unit boundaries as determined by independent field surveys (Guckian 1987). See Table 1 for map unit numerical and soil texture codes.

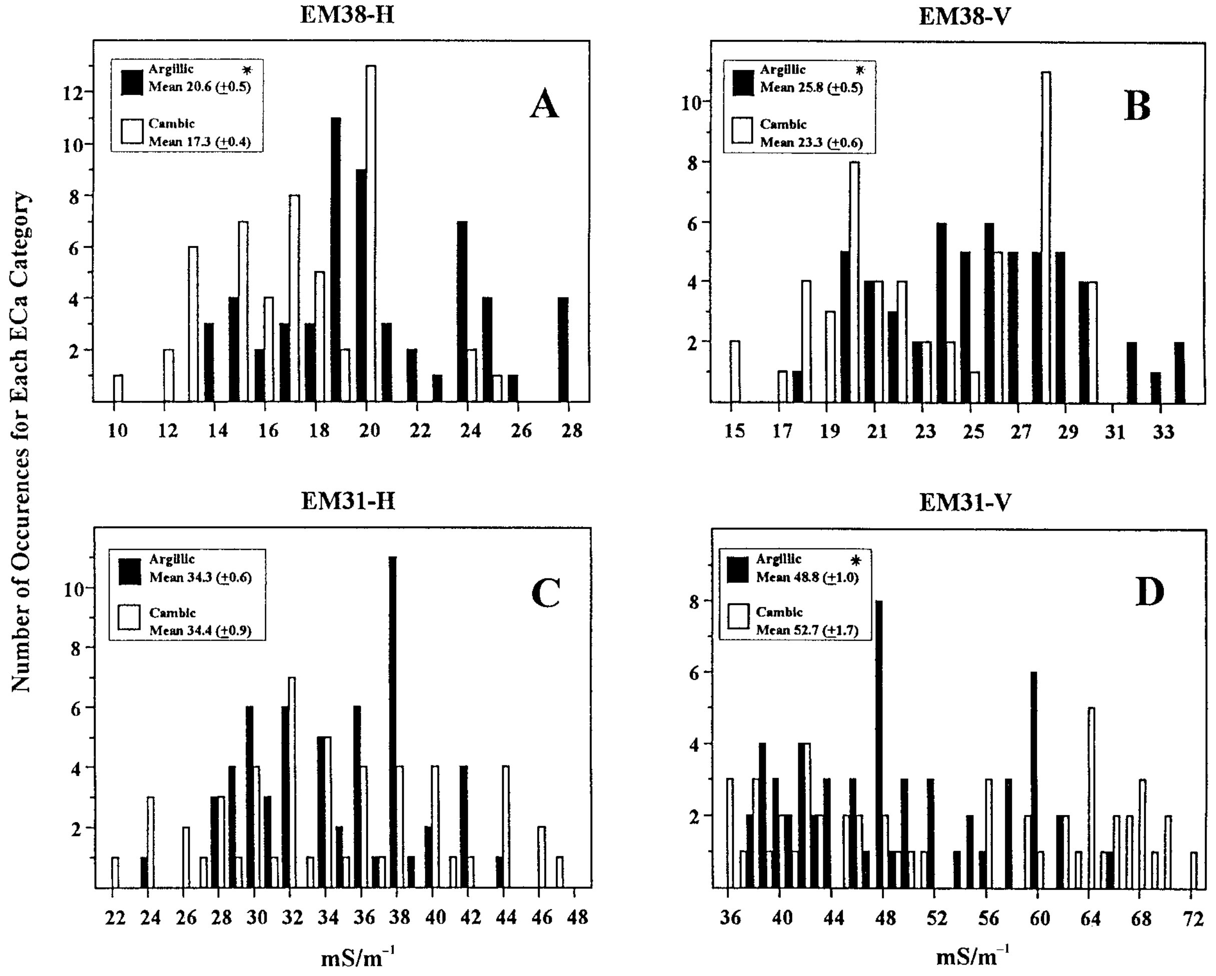

Figure 4. Apparent electrical conductivity values (mS m^{-1}) obtained with EM31 and EM38 meters on soils with argillic and cambic horizons. The '*' in the inset boxes denote significant logistic regression functions for distinguishing between the two horizons (see Table 4). Probability curves derived from these data are shown in Figure 5.

tive of the adjoining Lacoste–Olmos association were observed along the transect. The ability of EMI meters to consistently detect known soil series map unit boundaries and to potentially indicate within-map unit heterogeneity suggests this tool would be useful for coarse-scale survey and exploration applications.

Detection of cambic horizon inclusions

The detection of cambic inlusions within a laterally co-extensive argillic horizon was of particular interest to us, because of the importance of this feature in regulating vegetation patterns within upland portions of this savanna parkland landscape (Archer 1995). With the exception of the EM31 in the horizontal dipole mode, apparent conductivity measured on soils with cambic horizons differed from those with argillic horizons (Figures 4 and 5, Table 4). The EM38 meter, with a theoretical observation depth of 1.5 m, had the most appropriate observation depth for the phenomenon of interest (the presence/absence of an argillic horizon at ca. 40–100 cm). Logistic regression functions showed that distinctions between poorly expressed and well-developed argillic horizons were sharpest with the EM38 meter (Figure 5). For the deeper-sensing EM31 meter, distinctions between cambic and argillic soils based on ECa values were apparent only in the vertical diploe mode. With the EM38 meter, low values of apparent conductivity were indicative of a cambic horizon, whereas high values were indicators of the presence of a well-developed argillic horizon. The reverse was true for the deeper-sensing EM31-V read-

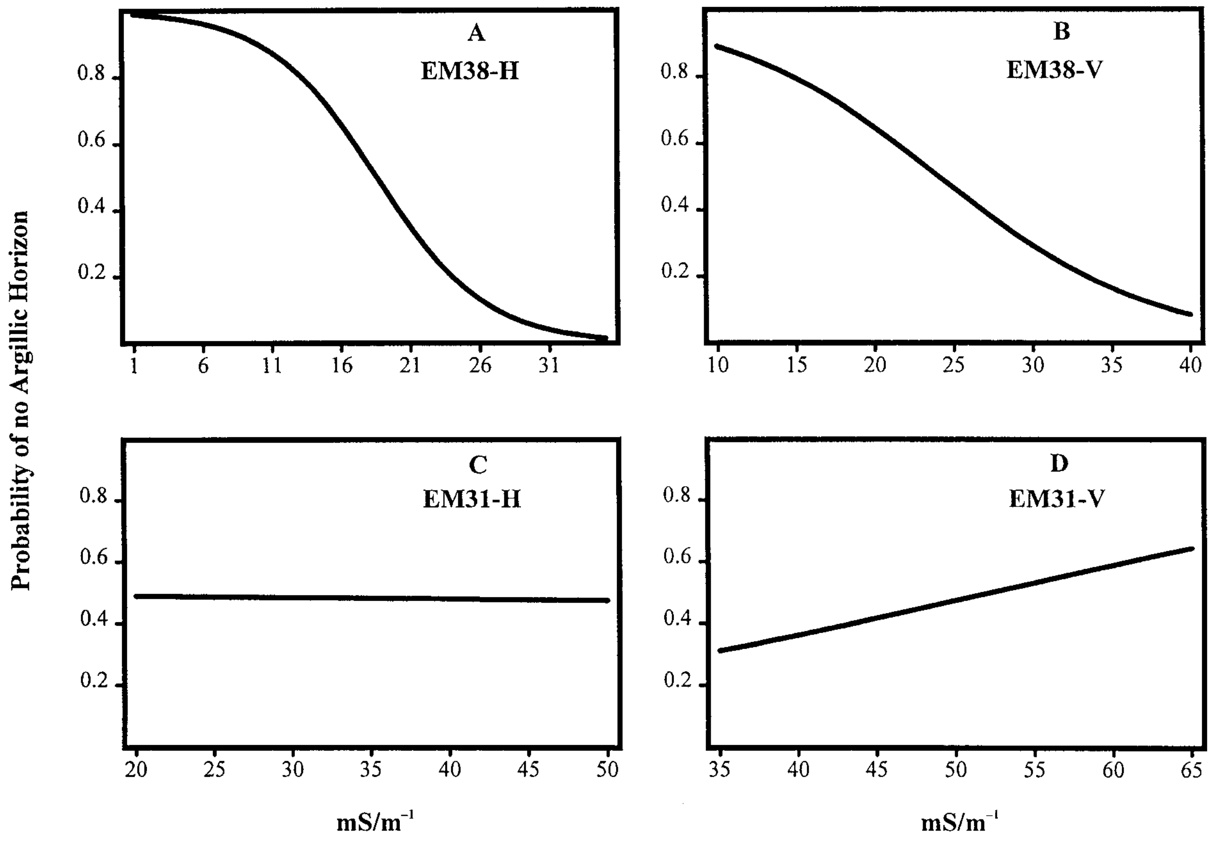

Figure 5. Probability of no argillic horizon based on logistic regression of ECa readings obtained with EM31 and EM38 meters in the horizontal (H) and vertical (V) dipole positions (Figure 4). See Table 4 tar statistical summaries. ECa values on the x-axis represent the range of values recorded for each instrument.

ings. Intermediate ECa values suggest that transitions between the cambic soils of grove interiors and the argillic soils of beyond grove canopy margins were gradual rather than sharp or abrupt. This interpretation has been borne out in subsequent soil sampling (Stokes 1999).

Armed with this predictive capability, we then used the EM38 to survey upland portions of the La Copita landscapes and prospect for non-argillic inclusions not occupied by obvious 'groves' of woody vegetation. Two such occurrences were found on the three uplands surveyed. In each instance, the vegetation was characterized by herbaceous vegetation and small discrete clusters of short woody vegetation. These clusters were qualitatively similar to those occurring where the argillic horizon was present and were markedly different from the well-developed groves whose non-argillic soils supported larger woody plants at higher densities (Archer 1995). An example of one of these non-argillic inclusion areas is shown in Figure 6. Figure 7 shows woody plants preferentially establishing and developing on the same non-argillic inclusion between 1941 and 1955. The shrub cluster continued to enlarge over the 45 years, but by 1990, woody plants had not yet fully occupied the inclusion.

Table 4. Logistic regression results predicting the presence/absence of an argillic horizon from apparent conductivity (ECa, mS m^{-1}), as measured with electromagnetic induction meters (EM38 and EM31) in horizontal (H) and vertical (V) dipole modes. Regressions are based on 54 readings from grids on two upland landscapes at the La Copita Research Area. See Figure 4 for graphical representation of data.

	Maximum scan depth (m)	b_0 intercept	b_1 parameter estimate	Standard error of estimate	Chi-square	Sig. level
EM38-H	0.75	4.756	−0.256	0.066	18.03	0.01
EM38-V	1.5	3.585	−0.149	0.051	9.303	0.01
EM31-H	3	−0.004	−0.002	0.036	0.003	ns
EM31-V	6	−2.404	0.046	0.02	5.415	0.02

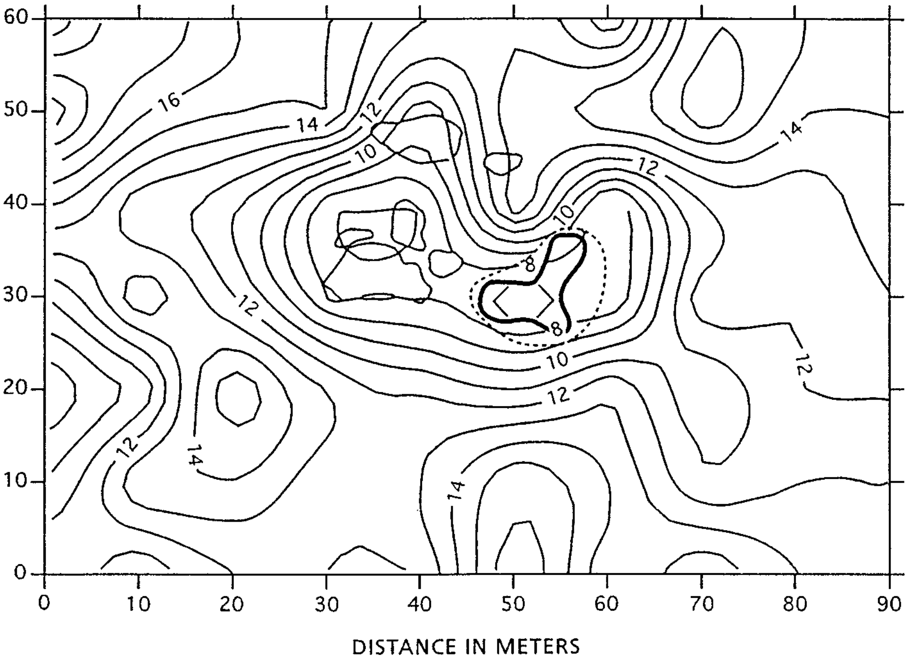

Figure 6. Two-dimensional contour plot (2 mS m^{-1} intervals) of ECa recorded with an EM38 meter in the horizontal dipole mode. The location of a cambic inclusion confirmed by field sampling (dotted line) and the areal extent of shrub cluster canopies in 1990 (thick solid lines) is also shown. Numbers on the *x* and *y* axes represent distance in meters. Note that shrub clusters are concentrated in areas where the argillic horizon is poorly expressed.

These results are significant on several counts. First, they are consistent with tree ring, soil δ^{13}C and simulation modeling reconstructions which indicate that the La Copita site was an open grassland which has experienced woody plant encroachment that began about 100 years ago and is still in progress (Archer 1995). Second, the fact that shrubs have only partially occupied non-argillic inclusions helps explain observations made on historical aerial photographs from 1941–present. These photos showed that some groves have grown continuously over the past 50 years, whereas others have exhibited no growth (J.C. Stroh and S.R. Archer, in prep.). We propose that the patches located with our EM38 prospecting (e.g., Figure 6) represent 'incipient groves' where woody plant patch expansion has only recently started (Figure 7) and where it will likely continue and at a rate greater than that which occurs where woody plants have already fully occupied the non-argillic inclusions. Thus, our results help explain the basis for the variation in patterns and rates of woody plant encroachment across these landscapes. In addition, EMI enabled us to locate specific patches for subsequent monitoring, experimentation and hypothesis testing.

Finally, there is ongoing debate as to whether the non-argillic inclusions on this savanna parkland landscape are: (H1) pre-existing conditions exploited by encroaching woody plants; (H2) the result of argillic horizon obliteration by burrowing organisms (cutter ants, rodents) attracted to a patch subsequent to woody plant establishment; or (H3) the result of long-term (thousands of years) occupation by woody plants which prevented formation of an argillic horizon (for example, by reducing clay eluviation via rainfall interception and transpirational pumping of water or by translocating carbonates from deep to shallow soils and thereby floculating clays). Detailed soil analyses by Loomis (1989) and δ^{13}C analysis of soil carbon (Boutton et al. 1998) have discounted H2 and H3. The 'incipient grove' sites located in our EM38 survey lends support to H1 and fails to support H2 (we saw no visual evidence of extensive faunal activity in the small shrub clusters which occupied the prospected non-argillic inclusion sites) and H3 (woody plants were small and young, based on size/age relationships of Stoker and Archer (1996); in the case shown in Figure 7, they were ca. 50 yr of age). The use of EMI as a prospecting device has thus given us a unique insight and another tool which can be used to help evaluate

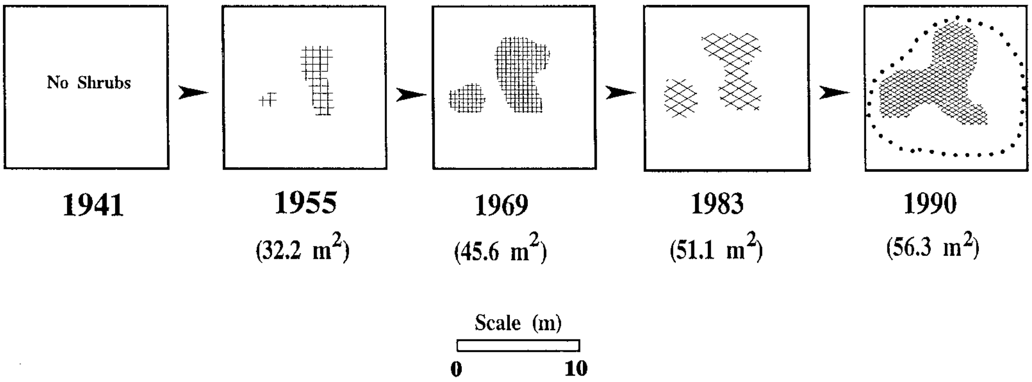

Figure 7. Spatial-temporal pattern of grove development within a cambic inclusion at the La Copita site. The cambic inclusion (indicated by the dotted line in the 1990 box) was initially located from EMI surveys of uplands, and its boundaries subsequently confirmed with soil sampling. The georeferenced location of the inclusion was then used to locate that same area on historical aerial photographs. Values in parentheses given below dates show areal extent (m^2) of shrub cover.

competing hypotheses of landscape organization and plant-soil relationships.

Conclusions

Information on subsurface heterogeneity will be required if we are to spatially constrain models of plant succession and realistically portray edaphic mediation of vegetation dynamics and change. In our example from the La Copita savanna parkland site, a knowledge of the size, shape and location of cambic inclusions not yet colonized or fully occupied by woody plants is important to anticipating the future pattern of landscape vegetation, the potential maximum extent of woody plant canopy coverage, and the growth rates and species interactions of woody plants (Archer 1995). Ground penetrating radar was not effective for characterizing subsurface edaphic features known to influence woody plant distribution at the La Copita site, because strong reflectance from fine-textured, near-surface soils obscured signal reflectance from deeper horizons. In contrast, electromagnetic induction (EMI) was useful for distinguishing between soils with cambic pedogenic horizons and those with argillic horizons. Given the importance of argillic horizons in regulating vegetation distribution and development on this savanna parkland (Archer 1995) and that of other arid and semi-arid communities (McAuliffe 1994). tools such as EMI have significant potential for enabling rapid, extensive screening of plant-soil relationships across landscapes where the depth and development of this horizon may vary. EMI was also effective in differentiating soil map units in, locating soil map unit boundaries and in identifying patches of subsoil heterogeneity within map units. Our applications add to a small, but growing list of uses in plant and landscape ecology [see Kawasaki and Osterkamp (1988) for estimating depth to permafrost; McBride et al. (1990) for evaluation of edaphic properties and forest site productivity; Kitchen et al. (1996) for sand deposition resulting from flooding; Boettinger et al. (1997) and Bork et al. (1998) for depth to restrictive horizons].

The physicochemical soil properties within a soil profile which influence apparent conductivity remain unclear. Our data further indicate that EMI instruments with different theoretical observation depths differed in their ability to distinguish subsurface features related to argillic horizon development and map unit boundaries. Thus, it is important to use EMI meters with observation depths most appropriate for the phenomenon of interest. Signal output can be affected by numerous soil features, including ephemeral variables such as moisture content (Williams et al. 1990). It is therefore necessary to ground-truth readings for specific applications and to interpret readings in relative rather than absolute terms. The light weight, maneuverability and portability of the battery operated EMI meters makes them suitable for pedestrian surveys and transport via all terrain vehicles. Even in dense shrublands, such as those at our study site, the instrument can be set up and read in a matter of minutes. When used in conjuction with a global positioning system, EMI technology has the potential for spatially explicit, large-scale survey and exploration applications in plant ecology, especially in regions where detailed soil surveys may not be available.

Acknowledgements

We thank Robert Flinn, Steve Watts, Steve Zitzer, Richard Drees, Ramero Molina (USDA/NRCS), Tony McKinney and the staff of the Texas A&M Soil Characterization Lab for help in field data collection and soil analysis. Neil MacDonald and Mel Northup made helpful comments on portions of the manuscript. This research was conducted in connection with grants from NSF Ecosystems (BSR-9109240), NASA-EOS (NAGW-2662) and The Texas Nature Conservancy.

References

Archer, S. 1995. Tree-grass dynamics in a *Prosopis*-thornscrub savanna parkland: reconstructing the past and predicting the future. Ecoscience 2: 83—99.

Archer, S., Boutton, T. W. and Hibbard, K. A. 2001. Trees in grasslands: biogeochemical consequences of woody plant expansion, In: Global Biogeochemical Cycles in the Climate System. pp. 115–137. Edited by E.-D. Schulze, S.P. Harrison, M. Heimann, E. A. Holland, J. Lloyd, I. C. Prentice and D. Schimel. Academic Press, San Diego, CA, USA.

Ammons, J. T., Timpson, M. E. and Newton, D. L. 1939. Application of aboveground electromagnetic conductivity meter to separate Natraqualfs and Ochraqualfs in Gibson County, Tennessee. Soil Survey Horizons 30: 66–70.

Boettinger, J. L., Doolittle, J. A., West, N. E., Bork, E. W. and Schupp, E. W. 1997. Nondestructive assessment of rangeland soil depth to petrocalcic horizon using electrogmagnetic induction. Arid Soil Res. Rehabilit. 11: 375–390.

Bork, E. W., West, N. E., Doolittle, J. A. and Boettinger, J. L. 1998. Soil depth assessment of sagebrush grazing treatments using electromagnetic induction. J. Range Manag. 51: 469–474.

Boutton, T. W., Archer, S. Midwood, A. J, Zitzer, S. F. and Bol, R. 1998. δ^{13}C values of soil organic carbon and their use in documenting vegetation change in a subtropical savanna ecosystem. Geoderma 82: 5–41.

Brady, N. C. 1984. The nature and property of soils. Macmillan, New York, NY, USA.

Bresler, E. B., McNeal, B. L. and Carter, D. L. 1932. Saline and Sodic Soils, Principles-Dynamics-Modeling. Springer-Verlag, New York, NY, USA.

Brus, D. J., Knotter, M., van Dooremolen, W. A., van Kernebeek, P. and van Seeters, M. J. M. 1992. The use of electromagnetic measurements of apparent soil electrical conductivity to predict the boulder clay depth. Geoderma 55: 79–93.

Cannon, M. E., McKenzie, R. C. and Lachapelle, G. 1994. Soil salinity mapping with electromagnetic induction and satellite-based navigation methods. Can. J. Soil Sci. 74: 335–343.

Collins, M. E. and Doolittle, J. A. 1987. Using ground-penetrating radar to study soil microvariability. Soil Sci. Soc. Am. J. 51: 491–493.

Cook, P. G., Walker, G. R., Buseli, G., Potts, I. and Dodds, A. R. 1992. The application of electromagnetic techniques to ground water recharge investigations. J. Hydrol. 130: 201–229.

Corwin, D. L. and Rhoades, J. D. 1990. Establishing soil electrical conductivity-depth relations from electromagnetic induction measurements. Commun. Soil Sci. Plant Anal. 21: 861–901.

Daniels, D. J., Gunton, D. J. and Scott, H. F. 1988. Introduction to Subsurface Radar. IEE Proceedings, 135:(F4) 278 – Geophysical Methods. National Water Wells Association, Dublin, OH, USA, pp. 827–840.

de Jong, E., Ballantyne, A. K., Cameron, D. R. and Read, D. W. L. 1979. Measurement of apparent electrical conductivity of soils by an electromagnetic induction probe to aid salinity surveys. Soil Sci. Soc. Am. J. 43: 810–812.

Doolittle, J. A. 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. Soil Survey Techniques, SSSA Special Publication No. 20.

Doolittle, J. A., Ealy, G., Secrist, G., Rector, D. and Crouch, M. 1995. Reconnaissance soil mapping of a small watershed using EM and GPS techniques. Soil Survey Horizons 36: 36–94.

Doolittle, J. A., Sudduth, K. A., Kitchen, N. R. and Indorante, S. J. 1994. Estimating depth to claypans using electromagnetic inductive methods. J. Soil Water Cons. 49: 552–555.

El Youssoufi, M. 1992. Factors influencing recruitment of honey mesquite (*Prosopis glandulosa* var. *glandulosa*) in a savanna woodland, Texas. Ph.D. Dissertation, Texas A&M University, College Station, TX, USA.

Greenhouse, J. P. and Slaine, D. D. 1983. The use of reconnaissance electromagnetic methods to map contaminant migration. Ground Water Monit. Rev. 3: 47–59.

Guckian, W. J. 1987. Soils of the La Copita Research Area, map and legend. *In* Soils of the La Capita Research Area, Map and Legend. Edited by C. J.Scifres and B. H. Koerth. MP 1626, p. 6. Texas Agricultural Experiment Station, College Station, TX, USA.

Gujarati, D. 1992. Essentials of Econometrics. McGraw-Hill, New York, NY, USA.

Hendrickx, J. M. H., Baerends, B., Raza, Z. I., Sadig, M. and Chaudhry, M. A. 1992. Soil salinity assessment of electromagnetic induction of irrigated land. Soil Sci. Soc. Am. J. 56: 1933–1941.

Hosmer, D. W. and Lemesshow, S. 1988. Applied Logistic Regression. Wiley, New York, NY, USA.

Kachanoski, R. G., Gregorich, E. G. and Van Wesenbeeck, I. J. 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can. J. Soil Sci. 68: 715–722.

Kawasaki, K. and Osterkamp, T. E. 1988. Mapping shallow permafrost by electromagnetic induction - practical considerations. Cold Regions Sci. Technol. 15: 279–288.

Kitchen, N. R., Sudduth, K. A. and Drummond, S. T. 1996. Mapping of sand deposition from 1993 Midwest floods with electromagnetic induction measurements. J. Soil Water Cons. 51: 336–340.

Loomis, L. E. 1989. Influence of heterogeneous subsoil development on vegetation patterns in a subtropical savanna parkland, Texas. Ph.D. Dissertation. Texas A&M University, College Station, TX, USA.

McAuliffe, J. R. 1994. Landscape evolution, soil formation, and ecological patterns and processes in Sonoran Desert bajadas. Ecol. Monog. 64: 111–1148.

McBride, R. A., Gordon, A. M. and Shrive, S. C. 1990. Estimating forest soil quality from terrain measurements of apparent electrical conductivity. Soil Sci. Soc. Am. J. 54: 936–938.

McNeill, J. D. 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Geonics Limited.

McNeill, J. D. 1986. Geonics EM38 ground conductivity meter operating instructions and survey interpretation techniques. Geonics Ltd.

McNeill, J. D. 1991. Advances in electromagnetic methods for groundwater studies. Geoexploration 27: 67–80.

Mokma, D. L., Schaetzl, R. J., Doolittle, J. A. and Johnson, E. P. 1990. Ground penetrating radar study of ortstein continuity in some Michigan haplaquods. Soil Sci. Soc. Am. J. 54: 936–938.

Nettleton, W. D., Bushue, L., Doolittle, J. A., Endres, T. J. and Indorante, S. J. 1994. Sodium-affected soil identification in south-central Illinois by electromagnetic induction. Soil Sci. Soc. Am. J. 56: 1190–1193.

Rhoades, J. D. and Corwin, D. L. 1981. Determining soil electrical conductivity depth using an inductive electromagnetic soil conductivity meter. Soil Sci. Soc. Am. J. 45: 255–260.

Rhoades, J. D. and Corwin, D. L. 1990. Soil electrical conductivity: Effects of soil properties and application soil salinity appraisal. Commun. Soil Sci. Plant Anal. 21: 837–860.

SAS Institute. 1990. SAS/STAT user's guide. SAS Institute. Cary, NC, USA.

Scanlan, J. C. and Archer, S. 1991. Simulated dynamics of succession in a North American subtropical *Prosopis* savanna. J. Veg. Sci. 2: 625–634.

Scifres, C. J. and Koerth, B. H. 1987. Climate soils and vegetation of the La Copita Research Area. Texas Agric. Exp. Sta. Bull. MP-1626. College Station, TX, USA.

Shih, S. F. and Doolittle, J. A. 1984. Using radar to investigate organic soil thickness in the Florida Everglades. Soil Sci. Soc. Am. J. 46: 651–656.

Soil Survey Staff. 1981. Soil Survey Manual. Revised edition. U.S. Dept. Agric., Agric. Handb., 18 (Examination and description of soils in the field. Ch. 4 of unpublished Soil Survey Manual. J. Stroh, Private Collection).

Soil Survey Staff. 1984. Procedures for collecting soil samples and methods of analysis for soil survey. USDA-SCS Soil Survey Inventory Report 1.

Stoker, R. and Archer, S. 1996. Growth rate and age-class distribution of mesquite on contrasting soils. La Copita Research Area 1996 Consolidated Progress Report. Texas Agricultural Experiment Station-Corpus Christi.

Stokes, C. J. 1999. Woody plant dynamics in a south Texas savanna:pattern and process. Ph.D. Dissertation, Texas A&M University, College Station. TX, USA.

Thien, S. J. 1979. A flow diagram for teaching texture-by-feel analysis. J. Agron. Educ. 8: 54–55.

Truman, C. C., Perkins, H. F., Asmussen, I. E. and Allison, H. D. 1988. Using ground-penetrating radar to investigate variability in selected soil properties. J. Soil Water Cons. 43: 341–345.

USDA. 1979. Soil survey of Jim Wells County, Texas. US Department of Agriculture-Soil Conservation Service and the Texas Agriculture Experiment by Station.

Watts, S. E. 1993. Rooting patterns of co-occurring woody plants on contrasting soils in a subtropical savanna. M.S. Thesis, Texas A&M University, College Station, TX, USA.

Williams, B. G. and Baker, G. C. 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. Aust. J. Soil Res. 20: 107–118.

Williams, B. G. and Hoey, D. 1987. The use of electromagnetic induction to detect the spatial variability of the salt clay contents of soils. Aust. J. Soil Res. 25: 21–27.

Williams, B. G., Richardson, D. P. and Walker, J. 1990. Spatial variability of apparent electrical conductivity. Technical Memorandum 90/6. Commonwealth Scientific and Industrial Research Organization (CSIRO), Canberra, Australia.

Wollenhaupt, N. C., Richardson, J. L., Foss, J. E. and Doll, E. C. 1986. A rapid method for estimating weighted soil salinity from apparent soil electrical conductivity measured with an above ground electromagnetic induction meter. Can. J. Soil Sci. 66: 315–321.

Zalasiewicz, J. A., M. S. J. and Cornwell, J. D. 1985. The application of ground conductivity measurements to geological mapping. Quart. J. English Geol. 18: 136–148.