Estimating depths to claypans using electromagnetic induction methods

J. A. Doolittle, K. A. Sudduth, N. R Kitchen, and S. J. Indorante

ABSTRACT: Claypans restrict infiltration, influence the lateral movement of soil water and agrichemicals, and limit crop production. In many areas of the Midwest, quantification and mapping of the variations in the depth to claypans are important components for research on water-quality and crop production. In an area of Mexico soils in central Missouri, a high correlation between the observed depth to claypans and the response of the EM38 meter was observed. Equations were developed to infer depths and chart the topography of the claypan. Compared with traditional methods of observing this subsurface layer, EM techniques are noninvasive, less labor intensive, more economical and can produce large quantities of data in a relatively short period of time.

Electromagnetic induction (EM) techniques use electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is the weighted average conductivity measurement for a column of earthen materials to a specified observation depth (*7*). The averages are weighted according to the depth response function of the meter (*16*). This technology has been used by geologists and geophysicists to map glacial deposits, bedrock surfaces (*20*) and permafrost (*9*), estimate the thickness of clay deposits (13), locate sand and gravel deposits (*11*), predict soil water content (*8*), and for groundwater investigations (*2, 3, 7*). More recently, this technology has been used in soil science principally to identify, map, and monitor soil salinity and groundwater contamination (*4,5,6,14,16,19*). In addition, this technology has been used to identify sodium-affected soils (*1*) and to assess edaphic properties important to forest site productivity (*10*). These studies have documented that this noninvasive technique is facile, provides a large number of measurements for the interpretation of site conditions, and can be applied over broad areas and soil types.

Variations in electromagnetic response are produced by changes in the ionic concentration of earthen materials. Factors influencing the ionic concentration and conductivity of earthen materials include (i) moisture content, (ii) amount and type of ions in the soil water, (iii) and amount and type of clays in the soil matrix. In areas of salt-affected soils, it has been estimated that 65% to 70% of the electromagnetic response can be explained by the concentration of soluble salts (*19*). In nonsaline soils of humid areas, however, soil texture, moisture content, and cation exchange capacity are often the principal factors determining apparent conductivity (*8,10*). The apparent conductivity of soils increases with exchange capacity, moisture content, and clay content (*8,15*).

Generally, EM techniques have been used most successfully in areas where subsurface properties are reasonably homogeneous, the effects of one factor (clay, moisture, or salt content) dominates over the other factors, and variations in EM response can be related to changes in the dominant factor (*3*). In such areas information is generally gathered on the dominant factor, and assumptions are made concerning the behavior of the other factors (*2*).

In the midwestern United States, there are about 4 million tilled hectares of claypan soils (*17*). These soils exhibit a dense, fine-textured subsoil, which restricts infiltration and influences the lateral movement of soil water and agrichemicals. In many areas of the midwest, quantification and mapping of the depth to claypan are important components for research on water-quality and crop production. Collection of such data with a soil probe or auger is highly tedious and labor intensive, making it impractical to collect the large quantities of data necessary to implement comprehensive claypan mapping studies over large areas. This study was undertaken to compare the relationship between data on depth to claypan as inferred by EM methods with data collected by conventional sampling methods. To demonstrate the use and compatibility of

Figure 1. Using the EM38 meter to measure apparent conductivity

---

J.A. Doolittle is a soil specialist with the USDA-Soil Conservation Service, Chester, Pennsylvania, 19013; K. A. Sudduth is an agricultural engineer with the Cropping Systems & Water Quality Research Unit, USDA-Agricultural Research Service, Columbia, MO, 65211; N.R. Kitchen is a research assistant professor with the School of Natural Resources, University of Missouri, Columbia, Missouri, 65211; and S.J. Indorante is a soil survey project leader with the USDA-Soil Conservation Service, MLRA Soil Survey Office, Belleville, Illinois, 62220.

Trade names are used in this article to provide specific information and do not constitute endorsement by the authors.

J. Soil and Water Cons. 49 (6) 572-575

EM and computer-graphic techniques, EM responses and a developed regression equation were used to predict and map variations in the depths to claypan in an adjoining site. The use of these techniques for mapping the depth to a strongly contrasting soil horizon has not been previously reported.

Materials and methods

Equipment. A Geonics Limited, EM38 ground conductivity meter was used in this study. This meter is shown in Figure 1. Principles of operation have been described in detail by McNeill (*11,12*).

The observation depths of an EM meter are dependent upon intercoil spacing, transmission frequency, and coil orientation relative to the ground surface. The EM38 meter has a fixed intercoil spacing of about one meter. It operates at a frequency of 13.2 kHz. The meter integrates values of apparent conductivity over observation depths of 0 to 75 cm and 0 to 150 cm in the horizontal dipole and the vertical dipole orientations, respectively.

Study area

The study location was at the Missouri Management Systems Evaluation Area (MSEA) near Centralia, Missouri. The study site was in a fallow research plot on a west-facing backslope of a broad, low, upland divide with relatively low relief (< 2.5 m).

The study site was located in an area of Mexico (fine, montmorillonitic, mesic Udollic Ochraqualfs) soils (18) and included both eroded and overwash phases of Mexico soils on 1% to 3% slopes. Mexico soils formed in moderately-fine textured loess over fine textured till. Depth to water table is very deep (>180 cm). The mineralogy is dominated by smectitic clays. Typically, the surface layer is silt loam, but ranges from silt loam to silty clay loam depending on the degree of erosion and subsoil mixing by cultivation. The subsoil is silty clay loam, silty clay, or clay. It is not uncommon to have subsoil or claypan horizons with 50 to 60 percent clay. Because of differences in clay content, contrasts in electrical conductivity were assumed to exist between the surface and claypan horizon(s) of Mexico soils.

Depth to claypan varied because of erosion, deposition, and landscape position. Within the study site, the depth to claypan ranged from less than 10 cm to more than 100 cm. Variations in the thickness of the surface and subsurface layers and the contrasts in electrical conductivity between these layers and the claypan were considered the principal factors likely to influence the EM response.

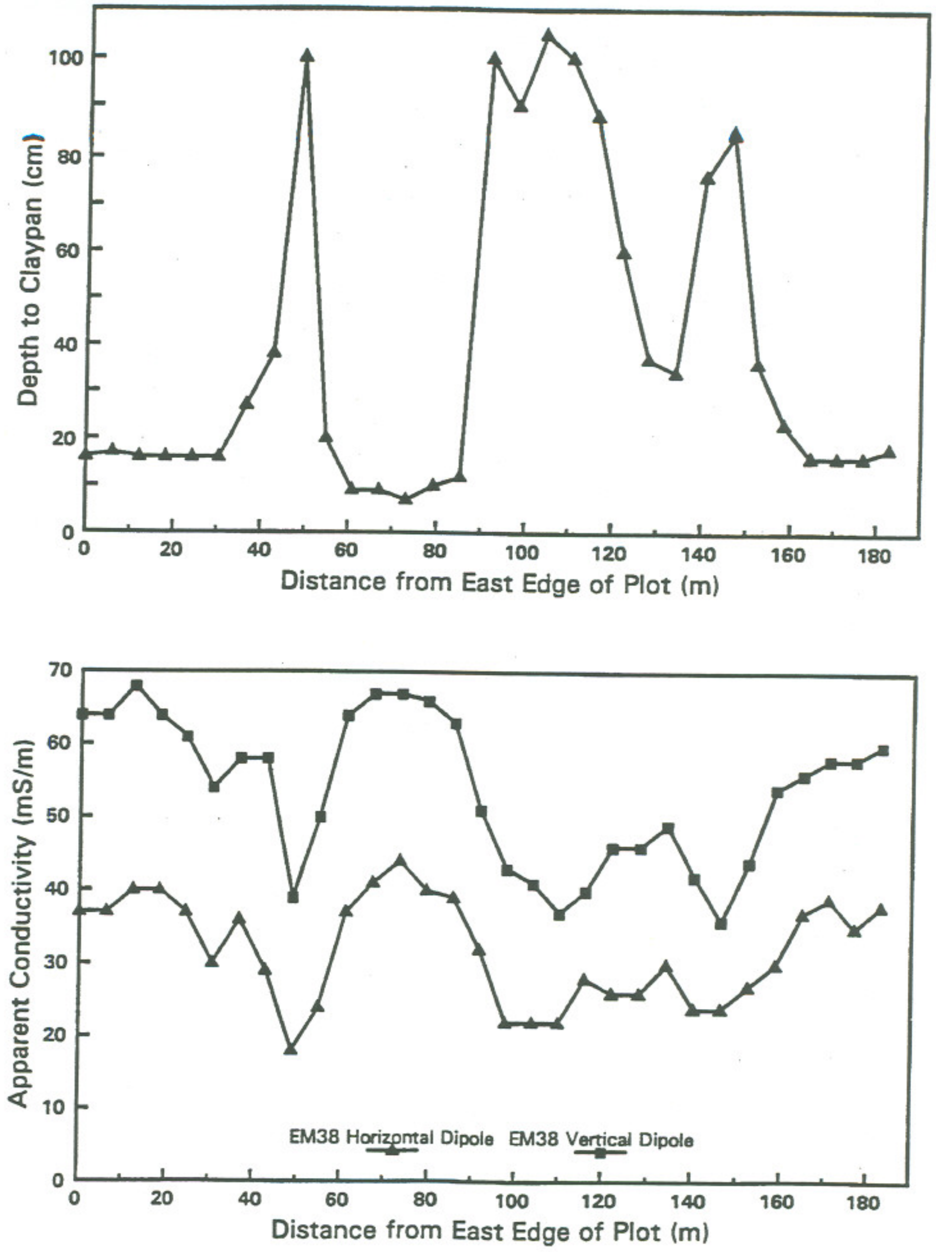

Figure 2. Depth to claypan (A) and apparent conductivity (B) along study transect

Field methods

A 190m transect line was established along the south border of plot 7 at the Missouri MSEA research site. Thirty-one observation points were flagged at 6.3 m intervals along this transect line. At each observation point, the depth to claypan was determined with a soil probe (4.1 cm diameter, 110 cm long). A characteristic sharp increase in clay content at the upper surface of the claypan was recognized by its resistance to the hand-probe and textural differences observed in the extracted cores. At each observation point, the EM38 meter was placed on the ground surface and measurements were taken in both horizontal and vertical dipole orientations. Depth to claypan measurements and EM data collected at each observation point along this line were compared and used to develop regression equations to predict the depth to claypan from values of apparent conductivity.

To demonstrate the use of EM techniques and developed regression equations to map the topography and depict variations in the depth to the claypan, a small, 12.2 by 18.3 m grid was established across the plot. The grid interval was 3.05 m. Survey flags were inserted in the ground at each of the 35 grid intersections. With the EM38 meter placed on the ground surface, measurements were taken in both horizontal and vertical dipole orientations at each grid intersection. Using the software program SURFER, two- and three-dimensional simulations of the site were constructed to help summarize predicted variations in the depth to claypan.

Results and discussion

Along the transect line, the depth to claypan averaged 39.6 cm and ranged from 7 cm to 105 cm (Figure 2A). The depth to claypan was shallow (<50 cm) at 71% and moderately deep (50 to 100 cm) at 26% of the observation points.

Values of apparent conductivity averaged 32 mS/m (milliSiemens/meter) and ranged from 18 mS/m to 44 mS/m in the horizontal dipole orientation (Figure 2B). In the vertical dipole orientation, values of apparent conductivity averaged 54 mS/m and ranged from 36 mS/m to 68 mS/m (Figure 2B). The higher readings in the vertical dipole orientation implied that apparent conductivity increased with soil depth. This relationship was believed to be a manifestation of increasing clay and moisture contents with depth.

Similar patterns existed in both depth to the claypan and apparent conductivity (Figures 2A and 2B). Generally, depth to claypan and apparent conductivity were inversely related (Figure 3). The coefficient of determination, r^2, between the depth to claypan and values of apparent conductivity was 0.635 (significant at the 0.005 level) in the horizontal dipole orientation and 0.727 (significant at the 0.005 level) in the vertical dipole orientation. Considering the large volume of soil measured with the EM38 meter to the volume of soil sampled with the probe, the correlation was considered favorable.

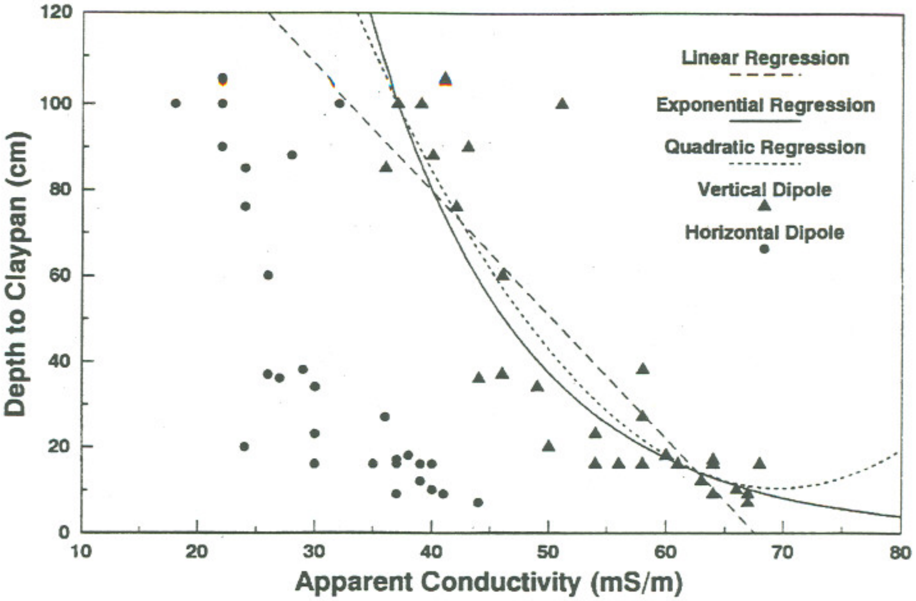

Figure 3. Relationship between measured depth to claypan and apparent conductivity values for study transect. Values of apparent conductivity collected with the EM 38 meter in the vertical dipole orientation. For regressions, refer to equations equations [1], [2], and [3] in text

At a given location, values of apparent conductivity obtained with the different coil orientations were strongly interdependent (r = 0.928). Since a stronger relationship existed between the apparent conductivity values obtained with the EM38

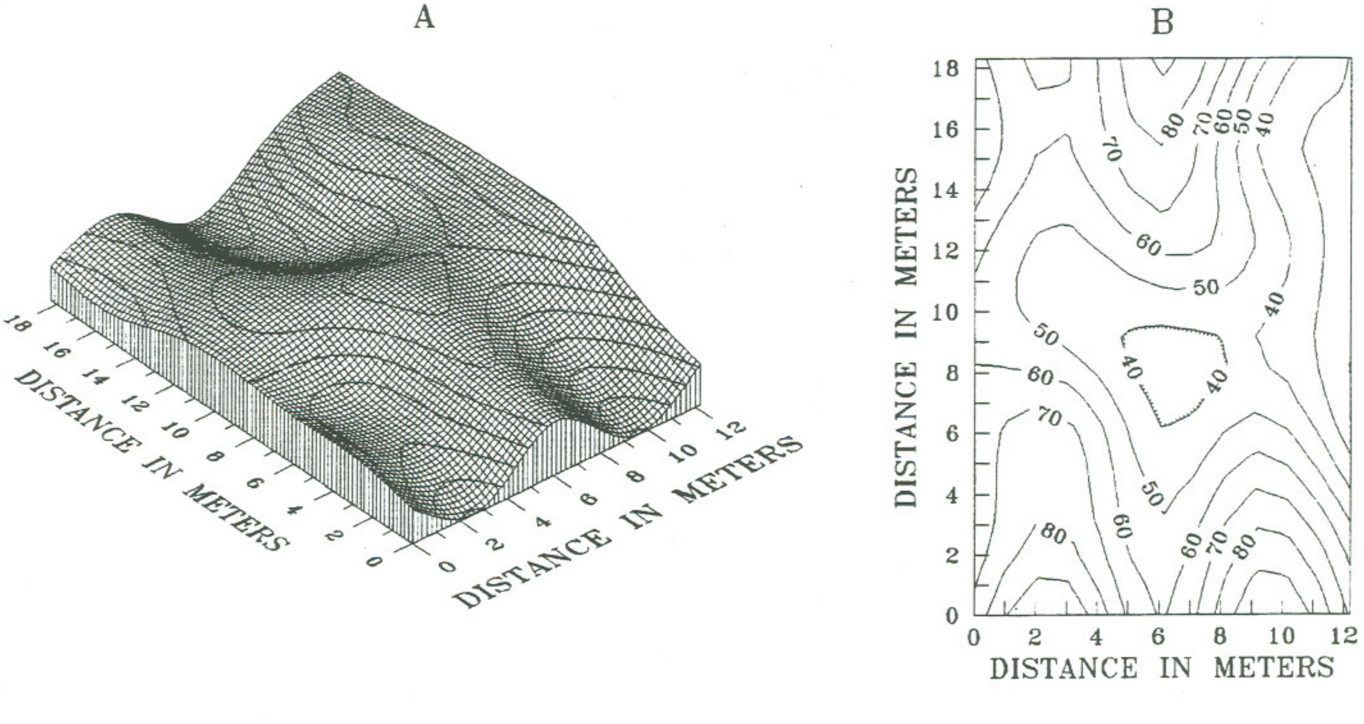

Figure 4. Three-dimensional surface net diagram of the claypan surface (A); Two-dimensional plot of the depth to the claypan (B); For each simulation, the contour interval is 10 cm

meter in the vertical dipole orientation and the depth to claypan, these values were used to develop regression equations to predict depth to claypan from apparent conductivity. The following equations were developed for the study site:

Linear regression ($r^2 = 0.73$):

$$D = 194.9 - 2.878\,X \qquad [1]$$

Quadratic ($r^2 = 0.77$):

$$D = 417.0 - 11.68\,X + 0.0839\,X^2 \qquad [2]$$

Exponential ($r^2 = 0.81$):

$$D = 1662\;10^{-0.033X} \qquad [3]$$

where D is depth to claypan (cm) and X is the apparent conductivity measured by the EM38 meter in the vertical dipole orientation (mS/m). An exponential regression equation appeared to be the best choice to predict the depth to claypan from values of apparent conductivity collected with the EM 38 meter in the vertical dipole orientation (Figure 3).

A large number of measurements can be collected with an EM meter in a very short period of time. Generally, at each observation point, EM measurements were recorded in less than 30 seconds. Empirical relationships between the depth to claypan and EM response can be developed from a limited number of observation points. Regression equations can be used to predict the depth to claypan over large areas.

Large quantities of data are needed to support soil information and modeling systems. Some of this information can be quickly and efficiently inferred with EM techniques. Large amounts of EM data can be processed and displayed on three-dimensional surface net diagrams (Figure 4A) or two-dimensional plots (Figure 4B).

Depths to claypan were estimated over a survey grid using EM38 vertical dipole data and the exponential regression equation [3]. Figure 4A is a three-dimensional surface net diagram of the topography of the claypan surface. The vertical scale has been exaggerated about 7.5 times. Figure 4B is a two-dimensional plot of the depth to claypan within the grid site. In both Figure 4A and 4B, the contour interval is 10 cm. These computer simulations can be used to summarize variations in the depth to the claypan, directions of lateral water flow, and facilitate the location of sampling sites. However, the accuracy of these simulations depends on the adequacy of the data used to construct the regression equations.

Conclusions

An EM technique was found to be useful for determining the depth to claypan at the Missouri MSEA study site. A high correlation was found between EM response and the depth to claypan in an area of Mexico soils under similar management practices. More investigations in other areas of Mexico soil are needed to establish the general form of the relationship. In order to assess the effects of differing soil moisture and temperature conditions, investigations need to include more extensive data sets collected at multiple claypan-soil sites and at different times of the year. It appears feasible, at least in some areas, to use EM methods and computer graphics techniques for mapping the depth to contrasting soil horizons and lithologic layers, thus enhancing our understanding of these subsurface features.

REFERENCES CITED

1. Ammons, J.T., M.E. Timpson, and D.L. Newton. 1989. *Application of an aboveground electromagnetic conductivity meter to separate Natraqualfs and Ochraqualfs in Gibson County, Tennessee.* Soil Survey Horizons 30(3):66-70.
2. Cook, P.G., M.W. Hughes, G.R. Walker, and G.B. Allison. 1989. *The calibration of frequency-domain electromagnetic induction meters and their possible use in recharge studies.* Journal of Hydrology 107:251-265.
3. Cook, P.G., G.R. Walker, G. Buselli, I. Potts, and A.R. Dodds. 1992. *The application of electromagnetic techniques to groundwater recharge investigations.* Journal of Hydrology 130:201-229.
4. Corwin, D.L., and J.D. Rhoades. 1982. *An improved technique for determining soil electrical conductivity-depth relations from above-ground electromagnetic measurements.* Soil Science Society of America Journal 46:517-520.
5. Corwin, D.L., and J.D. Rhoades. 1990. *Establishing soil electrical conductivity-depth relations from electromagnetic induction measurements.* Communications in Soil Science Plant Anal. 21(11&12):861-901.
6. De Jong, E., A.K. Ballantyne, D.R. Cameron, and D.W. L. Read. 1979. *Measurement of apparent electrical conductivity of soils by an electromagnetic induction probe to aid salinity surveys.* Soil Science Society of America Journal 43:810-812.
7. Greenhouse, J.P., and D.D. Slaine. 1983. *The use of reconnaissance electromagnetic methods to map contaminant migration.* Ground Water Monitoring Review 3(2):47-59.
8. Kachanoski, R.G., E.G. Gregorich, and I.J. Van Wesenbeeck. 1988. *Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods.* Canadian Journal of Soil Science 68:715-722.
9. Kawasaki, K. and T.E. Osterkamp. 1988. *Mapping shallow permafrost by electromagnetic induction—practical considerations.* Cold Region Science and Technology 15: 279-288.
10. McBride, R.A., A.M. Gordon, and S.C. Shrive. 1990. *Estimating forest soil quality from terrain measurements of apparent electrical conductivity.* Soil Science Society of America Journal 54:290-293.
11. McNeill, J.D. 1980. *Electromagnetic terrain conductivity measurements at low induction numbers.* Technical Note TN-6. Geonics Ltd., Mississauga, Ontario. p. 15.
12. McNeill, J.D. 1986. *Geonics EM38 ground conductivity meter operating instructions and survey interpretation techniques.* Technical Note TN-21. Geonics Ltd., Mississauga, Ontario. p. 16.
13. Palacky, G.J. 1987. Clay mapping using electromagnetic methods. First Break 5(8):295-306.
14. Rhoades, J.D. and D.L. Corwin. 1981. *Determining soil electrical conductivity-depth relations using an inductive electromagnetic soil conductivity meter.* Soil Science Society of America Journal 45:255-260.
15. Rhoades, J.D., P.A. Raats, and R.J. Prather. 1976. *Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity.* Soil Science Society of America Journal 40:651-655.
16. Slavich, P.G. and G.H. Petterson. 1990. *Estimating average rootzone salinity from electromagnetic induction (EM-38) measurements.* Australian Journal of Soil Research 28:453-463.
17. Smith, D.D. and D.M. Whitt. 1947. *Estimating soil losses from field areas of claypan soil.* Soil Science Society of America Proc. 12:485-490.
18. Soil Survey Staff. 1992. *Keys to Soil Taxonomy, 5th edition.* SMSS technical monograph No. 19. Blacksburg, Virginia. Pocahontas Press, Inc., p. 556.
19. Williams, B.G. and G.C. Baker. 1982. *An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards.* Australian Journal of Soil Reearch. 20:107-118.
20. Zalasiewicz, J.A., S.J. Mathers, and J.D. Cornwell. 1985. *The application of ground conductivity measurements to geological mapping.* Quarterly Journal of English Geology, London 18:139-148.

Single reprints of articles from the *Journal of Soil and Water Conservation* are available from the Soil and Water Conservation Society, 7515 Northeast Ankeny Road, Ankeny, Iowa 50021-9764, at a cost of $0.25 per page or a minimum of $5 per order.