Mapping the three-dimensional variation of electrical conductivity in a paddy rice soil

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Abstract

Soil salinity is widespread in a variety of environments, and land managers need to map its severity and extent both laterally and vertically from sample data. We have explored the use of apparent electrical conductivity (EC_a) measured with an EM38 conductivity meter and Tikhonov regularization to obtain conductivity profiles. We then used geostatistics to predict the conductivity between sampling points in coastal saline paddy land in the Yangste delta of China.

The EC_a matched closely the directly measured conductivity (EC_b) using the WET sensor system near the surface of the soil. Discrepancies increased down the profile to a maximum at about 80 cm, below which they converged again, and were judged small enough for monitoring purposes and to map soil salinity. The EC_a was determined with the EM38 at 56 positions in an adjacent field at 10 depths down to 110 cm, and the data analysed geostatistically. A linear model of coregionalization was used to cokrige the EC_a on a fine grid from which maps were made. The results revealed an irregularly shaped patch of salinity, serious at the base of the soil but of diminishing size and severity nearer to the soil surface.

Keywords

Saline soils; EM38; electrical conductivity; cokriging.

Introduction

Soil salinity, both natural and man-made, is widespread in the world and presents problems for agriculture. It retards the growth of crops and constrains production. In severe cases salinization causes land to be abandonned. Salts can rise to the soil surface by capillary transport from the water table and then accumulate as a result of evaporation. In many places they are concentrated by irrigation with salty water or by over-irrigation and the raising of saline ground water. According to Yu *et al.* (1996) the salt profile of the upper 100 cm is a good diagnostic of the suitability of the soil for arable crops. So, anyone assessing soil for farming needs to consider simultaneously the lateral and vertical variation in salt concentration. He or she needs to be able to describe and map three-dimensional distributions.

The three-dimensionality of soil is widely acknowledged. Thousands of papers and reports record variation down profiles. They are often linked to soil surveys, the principal results of which are displayed qualitatively as two-dimensional maps. Again there are thousands of them. In recent years geostatisticians have taken a more quantitative approach; they have analysed the lateral variation of individual properties and mapped them. But even when they have recognized vertical variation they have usually treated the soil as a series of independent layers; see, for example, Oliver and Webster (1987) and Samra and Gill (1993). Van Meirvenne e*t al*. (2003) were exceptional in this respect; they analysed the three-dimensional distribution of nitrate in the soil in an agricultural field. Their study and later one by He *e*t *al*. (2009) are the only ones of which we know in soil science.

We can think of several reasons why pedometricians have been reluctant to study soil properties in three dimensions at the field scale. One is the difficulty of visualization; how do you display the results of three-dimensional interpolation? Another is the gross anisotropy, with differences in scale of several orders of magnitude between lateral and vertical distances. Strong drift in the vertical dimension adds to the difficulties. Finally, even if you overcome those difficulties you have the cost of obtaining data to consider; the cost of drilling or inserting probes into the ground at numerous sampling points has been prohibitive in the agricultural context.

Surveys of salinity, however, have been revolutionized by the development of sensors based on electromagnetic induction (EM) with equipment such as the EM31 and EM38 (McNeill 1980). The EM38 is the more useful for agricultural applications because its penetration to 1.5 m corresponds roughly with the rooting depth of many crops, and it is much used. The technique has a further attraction, for by using a linear model of the response of the instrument and second-order Tikhonov regularization one can estimate conductivity profiles (Borchers *et al.* 1997; Hendrickx *et al.* 2002).

We have explored the combination of the Tikhonov regularization of EM38 data and geostatistical analysis to estimate the soil's EC_a in three dimensions in a coastal region of China where salinity is a problem. We describe our experience below.

The region, sampling and measurement

Study area

The land in the coastal zone of Zhejiang Province south of China's Hangzhou Gulf of the Yangtse delta is formed of recent marine and fluvial deposits. The soil is dominantly light loam or sandy loam with a sand content of about 60%. It is also saline, with large concentrations of Na and Mg salts (in many places >1%). For this study we chose a field of 2.22 ha that was reclaimed in 1996 and used for paddy rice. Its coordinates are 30°9′N, 120°48′W. Figure 1 shows it as 'Field A' with its neighbor 'Field B' and its general location.

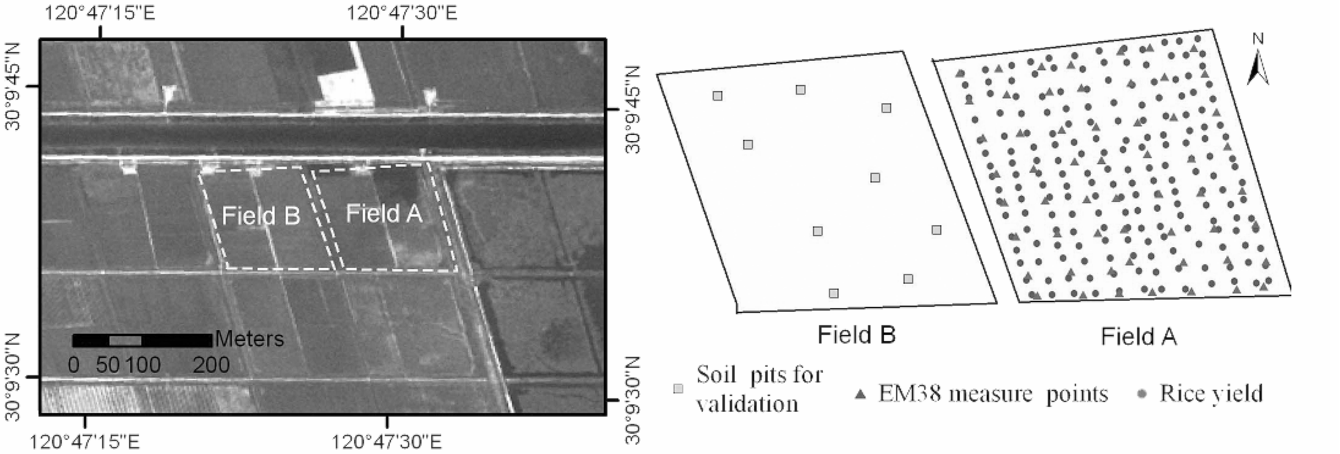

Figure 1. Location of the region studied and the positions of the sampling points in the field.

Sampling and measurement

We measured EC_a with the Geonics EM38 conductivity meter at 56 places in Field A roughly on a grid at intervals of approximately 23 m; again see Figure 1. We did so after the rice had been harvested in December 2006. Each position was georeferenced by a GPS. At each we took 96 EM38 readings, as follows.

The EM38 device was placed with its centre over the grid node. Readings were made on two instruments, one with the coils configured horizontally (EM_H) and the other vertically (EM_V). Each instrument was then raised, starting from 0, when it was on the ground, to heights 10, 20, 30, 40, 50, 60, 75, 90, 100, 120 and 150 cm above the soil surface. To validate the measurements from the EM38 we dug pits 110 cm deep at nine positions in the adjacent Field B. In each pit we measured the bulk electrical conductivity (EC_b) using the WET sensor system at 5, 15, 25, 35, 45, 55, 67.5, 82.5, 95 and 110 cm below the surface. In this way we obtained accurate data of electrical conductivity down the soil profile against which to judge the worthiness of the EM38 readings.

At harvest time, on 20 October 2006, we collected the yield of rice plants at each of 192 sampling points in Field A (see Figure 1 for their positions) for compare the distribution of soil salinity.

Conductivity profiles

Linear model and its inversion

McNeill (1980) described the linear model used to predict the response of the EM38 instrument at a height above the ground from the electrical conductivity down the soil profile. The response of the instrument consists of a system of two Fredholm equations:

$$m_H(h) = \int_0^\infty \phi_H \ (u+h)\eta(u)du \qquad (1)$$

and

$$m_V(h) = \int_0^\infty \phi_V \ (u+h)\eta(u)du \qquad (2)$$

In these equations the subscripts H and V denote respectively the horizontal and vertical orientations of the coils in the instrument, and $m_H(h)$ and $m_V(h)$ represent the measured values at height h above the ground with those two orientations. The quantity $\eta(u)$ is the conductivity at depth u in the soil, and ϕ_H and ϕ_V, the sensitivities for the horizontal and vertical orientations of the coils, are given by McNeill (1980) .

Procedure and results

Borchers *et al*. (1997) have provided code in MATLAB for the computations. We used their code for the linear model, Equations (1) to (4), to predict the EM38 readings at heights 0, 10, 20, 30, 40, 50, 60, 75, 90, 100, 110, 120 and 150 cm above the ground and then to invert the predictions by the Tikhonov regularization. In this way we obtained apparent conductivities, EC_a, at the same depths as those at which we measured the bulk conductivity, EC_b, by the WET sensor, i.e. at 5, 15, 25, 35, 45, 55, 67.5, 82.5, 95 and 110 cm.

Figure 2 shows the calculated apparent conductivities, EC_a, and compares them with the measured bulk conductivities, EC_b, for the two profiles selected from all profiles. The conductivities varied greatly with depth; EC_b ranged widely from 15 to 296 mS m^{-1} . Most profiles became increasingly salty with increasing depth, though in several the conductivity was greatest in the upper part of the subsoil. There is reasonably close agreement between EC_a and EC_b for most of the profiles, similar to that reported by Borchers *et al.* (1997). There are, however, fairly large discrepancies for others.

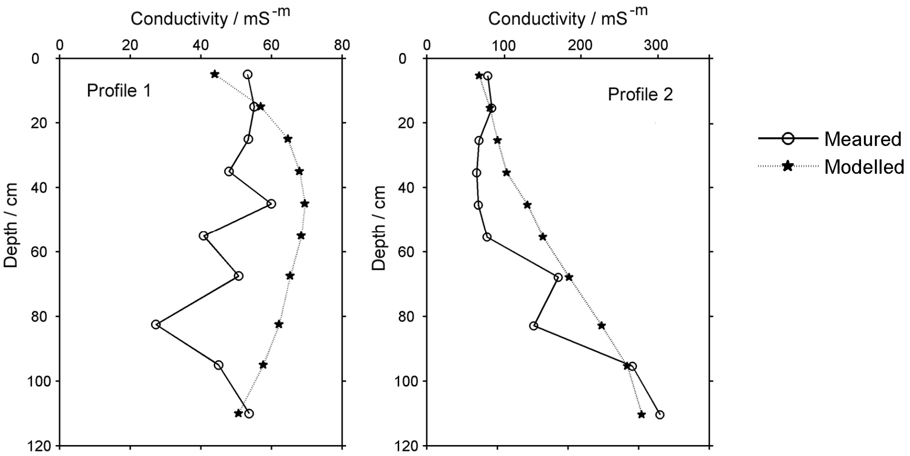

Figure2. Profiles of mean bulk electrical conductivity EC_b and conductivity predicted by Tikhonov regularization from EM38 measurements

Hendrickx *et al.* (2002) presented similar results showing that measurements made with the EM38 followed by Tikhonov regularization gave results that matched well the measured conductivity for values less than 100 mS m^{-1}. They also found that a more elaborate non-linear model gave somewhat closer matches, but the improvement was so small that they judged it not worth the much greater computational demand.

Given the above results and the experience of Hendrickx *et al.* we decided to use the measurements from the EM38 and the Tikhonov inversion of the linear model to obtain values of the apparent electrical conductivity, ECa, to characterize the salinity in Field A. We use these values to map the salinity, and we describe the procedures and results in the next section.

Geostatistics

The maxima, means and medians of EC_a at the 56 sites in Field A increase with increasing depth; there is a strong trend in the vertical dimension. In fact, there appears to be an almost linear trend at every sampling point. Further, there is strong correlation between all pairs of depths, especially between adjacent layers. In these circumstances it seems that the best way to map the salinity is to treat the EC_a at the 10 depths as 10 coregionalized variables and to fit a linear model of coregionalization to their variograms.
All auto-and cross-variograms for the 10 depths were computed by the usual method of moments. For the 10 depths this gave 10 autovariograms and 35 cross-variograms. Variation appeared isotropic, and so we represented the lag in distance only and incremented it at 10-m intervals. The auto-variograms appear as sequences of black discs. They are remarkably similar in form; only the scale of variance changes appreciably. The cross-variograms are also similar, and do not merit display.

We had then to choose and fit a linear model of coregionalization to the complete set of variograms. A power function would be the most suitable model, and so that plus a nugget variance provided the basic structures. The next step was to estimate the EC_a at all 10 depths. Although all depths were sampled at all 56 positions in the field we cokriged using all data to provide coherence. We computed block estimates for 5 m × 5 m squares at 5-m intervals over the whole field.

As above, we have to overcome the problem of vizualizing the kriged estimates in the three dimensions. Figure 3 is our solution in which we view the layers obliquely from above in sequence, starting at the base 110 cm deep and adding one layer at a time and showing the vertical variation on the southern and eastern faces of the field as the layers are added.

From Figure 3 we can see an irregularly shaped patch of saline soil (large ECa) in the lowest layer, the bottom left graph. The patch diminishes in extent and severity higher in the soil.

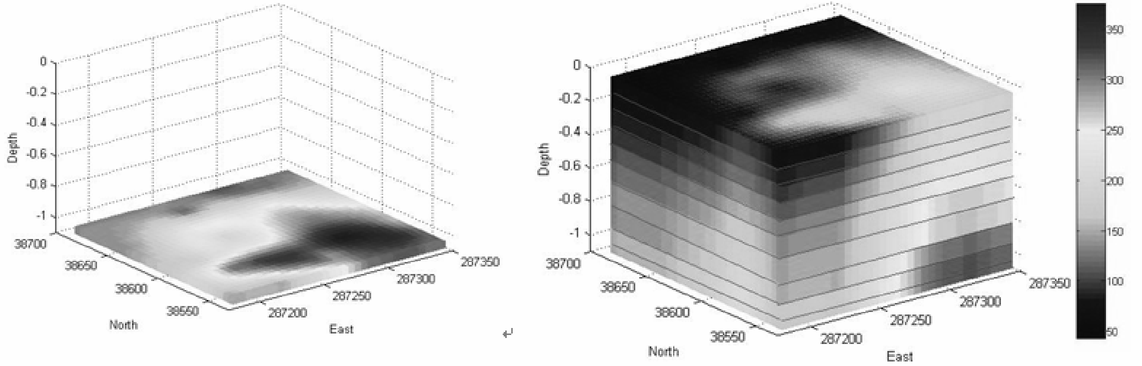

Figure 3. Block-kriged estimates of ECa in Field A at 10 depths from 110 cm, left, to 5 cm top right. Note the way that the large conductivity in the irregular patch at 110 cm diminishes upwards.

Conclusions

In the rice paddy we studied the Tikhonov inversion of the linear model from measurements made with the EM38 compared reasonably accurately with the direct measurements made with the WET sensor, and it gave us confidence in the use of the EM38 for mapping salinity to at least 1 m at the field scale. The strong correlation of EC_a down the profile and the consequently strong coregionalization enabled us to map conductivity as EC_a by cokriging 5 m × 5 m blocks in 10 layers down to 110 m with small errors. The result shows the potential of the EM38 device for land management and specifically for rapidly identifying and mapping soil that needs remediation or should not be planted with rice.

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