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Mapping the three-dimensional variation of soil salinity in a rice-paddy 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. In this research we explore the inversion of apparent electrical conductivity (EC_a) measured with an EM38 using a linear model and Tikhonov regularization to model electrical conductivity (σ) profiles in a saline paddy field in the Yangtze delta of China. The modelled σ matched closely the directly measured bulk electrical conductivity (σ_b) in the topsoil within our calibration field. Discrepancies were greatest between 0.4 and 0.8 m, below which they converged again, and were judged small enough to map soil salinity. Equivalent EC_a data, recorded in an adjacent field, was similarly inverted with the modelled σ analysed geostatistically. In this regard, the σ data at 10 depths were treated as 10 correlated variates, and experimental auto-and cross-variograms were computed by the method of moments from them. A linear model of coregionalization fitted well, and it was used to cokrige σ on 5 m×5 m blocks on a fine grid. The kriging errors, computed as the square roots of the cokriging variances, were typically about 5% of the kriged estimates. Estimates of σ were then converted into the universal standard of soil salinity measurement (i.e. electrical conductivity of a saturated soil paste extract − EC_e). The results indicate that an irregularly shaped patch of strongly saline topsoil (i.e. 8–12 dS m^{-1}) and subsoil salinity (i.e. >16 dS m^{-1}) at the southern end of the field was consistent with a yield reduction of some 33%; and as compared with the weakly saline conditions evident at the northern end of the field (e.g. topsoil EC_e 2–4 dS m^{-1}) where yield was much larger. We conclude that the approach has merit and might be useful in providing a baseline set of data and a method that can used to monitor and evaluate the management of salinity.

1. Introduction

Soil salinity, both natural and man-made, is widespread in the world and presents problems for agriculture. This is because salt retards the growth of crops and constrains production. In severe cases salinization causes land to be abandoned. Man–made or secondary salinization occurs as a result of the mobilization of salts stored naturally in the subsoil and into the root-zone (0–1 m). In irrigated areas, where water management is poor (i.e. over irrigation), the salt can be brought to the soil surface by capillary transport and from a rising water table. The problem is that the salt accumulates in the root zone as a result of evaporation and evapotranspiration. As such, and according to Funakawa and Kosaki (2007), the most serious threat for irrigated agricultural production, is the presence of soluble salts stored naturally and in the subsoil between 1 and 2 m.

The scientific literature contains many reports that show that the above scenario has occurred almost systematically in some semi-arid and arid areas in which irrigation has been developed for agriculture. However, and apart from a few investigations, there are very few case studies that illustrate similar processes in coastal lands reclaimed from the sea. One of these is the work of Yu et al. (1996) who found that the salinity profile of the upper 1 m is a good diagnostic indicator of the suitability of soil for arable crops. As a result, and to assess the suitability of soil for farming, a methodology is required to consider simultaneously the lateral and vertical variation in salt concentration. That is, a method is required to describe and map the three-dimensional distribution of soil salinity.

The three-dimensional nature of soil is widely acknowledged as attested by the thousands of papers and reports that record variation of soil properties down profiles. They are often linked to soil surveys, the principal results of which are displayed qualitatively as two-dimensional maps. In recent years geostatisticians have taken a more quantitative approach because they have been interested in analysing the lateral variation of individual properties and mapping them. But even when they have recognized vertical variation they have usually treated the soil as a series of independent layers (e.g. Oliver and Webster, 1987; Samra and Gill, 1993). More recently, pedometricians such as Van Meirvenne et al. (2003) have analysed the three-

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dimensional distribution of nitrate in the soil in agricultural fields. This and later studies by He et al. (2009) and Verstrate and Van Meirvenne (2008) are the only ones we know in soil science.

So why is it that soil has not been more universally mapped in three dimensions? We can think of several reasons why pedometricians have been reluctant to make such studies at the field scale. One is the difficulty of visualization; how do you display the results of three-dimensional interpolation? It is surmountable; miners and petroleum engineers have had to overcome it. 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 soil 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). This is because these sensors enable the soil's bulk apparent electrical conductivity (EC_a in mS m^{-1}) to be measured proximally and to depths of 6 m and 1.5 m from above the ground surface (Corwin and Lesch, 2003), respectively. Of these, the EM38 is the more useful for agricultural applications. This is because 70% of the instrument's response in a homogenous soil corresponds roughly with the rooting depth of many agricultural crops (i.e. 1.5 m). This is particularly the case in investigations and mapping of salinity in which the instrument first needs to be calibrated (e.g. Triantafilis et al., 2000) and then used to map its spatial distribution (e.g. Triantafilis et al., 2001).

These sensors have further attractions, for by using a linear model of the response of the instrument and second-order Tikhonov regularization one can model the true electrical conductivity (σ) of soil with depth and therefore of profiles (Borchers et al., 1997; Hendrickx et al., 2002; McBratney et al., 2000). Here we first explore Tikhonov regularization of EM38 EC_a data to estimate the true electrical conductivity (σ in mS m^{-1}). We compare our estimates of σ with measured bulk electrical conductivity (σ_b in mS m^{-1}) using a WET sensor. To generate a three-dimensional model of σ and to understand its lateral and vertical extent we use geostatistical analysis. Finally, we relate our linear modelled and kriged estimates of σ to soil EC_e so as to explain our results in terms of measured grain yield of a rice paddy crop and the salt tolerance of various other agricultural crops. This is because soil salinity is increasingly becoming a problem in the coastal region of China.

2. Site and methods

2.1. Study area

The land in the coastal zone of Zhejiang Province south of China's Hangzhou Gulf of the Yangtze delta is formed of recent marine and fluvial deposits. The soil consists predominantly of uniform profiles of light loam or sandy loam textures, with a sand content of about 60%. It is also saline, with large concentrations of Na and Mg salts (in many places >1%). The climate is subtropical with an average temperature of 16.5 °C and a mean annual rainfall of 1300 mm. The natural vegetation is evergreen broadleaf forest.

However, over the past 30 years and owing to (i) the favourable climate and (ii) an ever expanding population in the nearby cities of Hangzhou and Shanghai, much of this zone has been enclosed and reclaimed for agriculture. The fields we describe below were reclaimed in 1996 and were first used for irrigated cotton production. Since 2006, these fields have been used for rice paddy farming. However, whereas reclamation has been fairly successful, soil salinization is increasing, and countering it is becoming problematic. As such, methods and techniques are required to measure and monitor the dynamics of soil salinization so that the land can be managed in the future. To test the ability of the EM38 and Tikhonov regularization to provide this information we chose to study two fields of approximately 2.22 ha. The fields lie to the north of Shangyu City at 30°9′N, 120°48′E.

2.2. EC_a measurement with an EM38

As shown in Fig. 1, we first measured EC_a with a Geonics EM38 conductivity meter at 56 nodes in field A; roughly on a 7 m × 8 m grid and at intervals of approximately 20 m. We did so after the rice had been harvested in December 2006. Each position was georeferenced by a Trimble Global Positioning System. At each position we took 96 EM38 readings, as follows. The EM38 device, which is approximately 1 m long with a transmitter near one end and a receiver near the other, was placed with its centre over the grid node. Readings were made using two EM38 instruments; one with the coils configured horizontally (EM38h) and the other vertically (EM38v). The first EC_a measurements were made on the ground surface to provide values of the soil's EC_a to theoretical depths of 0–0.75 and 0–1.5 m, respectively.

Each EM38 was then oriented with its axis aligned from west to east (direction 0) and then rotated anticlockwise in steps of 45°, so that its later alignments were 45°, 90° and 135°. Each instrument was then raised, starting from 0, when it was on the ground, at 0.10 m increments between depths of 0.1 and 0.6 m and also at heights of 0.75, 0.9, 1.1, 1.2 and 1.5 m above the surface. This large set of EC_a data was recorded for input to the linear model described by Borchers et al. (1997) and which is used to estimate at discrete depth intervals by second-order Tikhonov regularization. The many EC_a measurements were made also to reduce the noisy nature of EM data.

To validate the estimates of σ, we dug pits to a depth of 1.1 m at nine positions in the adjacent field B. At each of these positions the same set of EM38 EC_a data, described above, was recorded. Fig. 1 shows where they were located. The three northern-most profiles are from east to west, profiles 1, 4 and 5. Profiles 6 and 9 as well as profiles 3 and 5 lie near the centre of the field, with profiles 2 and 8 at the southern end. Note that at the northern end of the field there is a large irrigation supply channel and at the southern end there is a smaller drainage ditch. In each pit we measured the bulk electrical conductivity σ_b of the soil samples and at the various depths using the WET sensor system (Delta-T Devices Ltd, Cambridge, UK) and at 0.10-m increments between depths of 0.05 and 0.55 m and also at depths of 0.675, 0.825, 0.95 and 1.10 m below the surface. The WET sensor is robust and portable and can be used in situ to measure both the water content and the EC of the soil.

In this way we obtained accurate data of σ_b down the soil profile against which to judge the worthiness of the estimates of σ inverted from the EM38 EC_a and using the linear model of Hendrickx et al. (2002). In addition, we also took soil samples at these depths so as to determine in the laboratory the electrical conductivity of a saturated soil paste extract (i.e. EC_e in dS m^{-1}). In this way we could assess the results of our modelled σ in terms of measurements of salinity which can be related to agricultural crops tolerances. Further to this, and to provide an agronomic assessment of the value of the estimates of σ, we collected grain at harvest time. That is, on 22 October 2011, we collected three rice plants at each of the 56 locations in field A and where we measured the EM38 EC_a. We separated and weighed the grain, and estimated the 1000-grain weight (in g).

2.3. Modelling σ from measured EC_a using a linear model with Tikhonov regularization

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

$$m_H(h) = \int_0^\infty \phi_H(u+h)\eta(u)\mathrm{d}u \quad (1)$$