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Modelling the electrical conductivity of soil in the Yangtze delta in three dimensions

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ABSTRACT

Numerous processes, past and present, have given rise to lateral and vertical variation in the soil and to its individual properties such as its salinity and electrical conductivity. The resulting patterns of variation are complex and appear to comprise both random and deterministic components. The latter dominates vertically as trends in most soil profiles, and in the situation we describe it is prominent in the horizontal plane, too. Describing this variation requires flexible choice of covariance function. The processes of model estimation and prediction by kriging in three dimensions are similar to those in two dimensions. The extra complexity of the three-dimensional variation requires practitioners to appreciate fully the assumptions that their choices of model imply and to establish ways of testing the validity of these assumptions. We have examined several covariance functions more commonly used to describe simultaneously variation in space and time and adapted them to model three-dimensional variation in soil. We have applied these covariance functions to model the variation in salinity in reclaimed land in the Yangtze delta of China where the apparent electrical conductivity (EC_a) has been measured at numerous points down to 1.1 m. The models take into account random and deterministic components in both the horizontal and vertical dimensions. The most suitable mixed model was then used to krige the EC_a on a fine grid from which three-dimensional diagrams of the salinity are displayed.

1. Introduction

It is now a common practice to use geostatistical methods to model the horizontal variation of soil properties and to predict values at unvisited sites by some form of kriging (Webster and Oliver, 2007). In many instances one can treat the variation as the outcomes of intrinsically stationary correlated random processes and model the variation satisfactorily with one or other of the popular authorized variogram functions. The random variation may be isotropic, so that one may disregard direction. Alternatively where the spatial correlation evidently varies with changes in direction one can often treat the anisotropy as geometric and elaborate the model in the form of a geometric anisotropic variogram function. Such a function permits the distance parameter(s) in the model to vary according to direction. If the variogram is bounded its sill is the same in all directions.

In three dimensions this assumption of a constant sill is much less likely to be appropriate for soil. The processes such as differential weathering, leaching and fluctuating ground water which lead to vertical variation differ substantially from the earth surface processes that act horizontally and on quite different spatial scales. This can lead to quite different horizontal and vertical sill variances, even after the removal of any trend components. More complex variograms or spatial covariance functions are required.

An analogous problem occurs when we model the variation of a property in both space and time, and several spatio-temporal correlation functions have been proposed (De Cesare et al., 2001; Kyriakidis and Journel, 1999).

In this paper we demonstrate that such functions can be used to represent the three-dimensional variation of a soil property, namely the soil's apparent electrical conductivity (EC_a) which is commonly used as a proxy for soil salinity. We do so with sample data on EC_a recorded in an ongoing investigation into the salinity in the Yangtze delta (Li et al., 2013, 2015).

2. The setting

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. Huge quantities of sediment are deposited in the delta each year, and as the delta builds so more of it can be empoldered and claimed for agriculture, in particular, for paddy rice. Rice will not grow well, if at all, in salty soil, however. Farmers, therefore, wish to be sure before they plant their rice that salt will not impair its growth. Farmers

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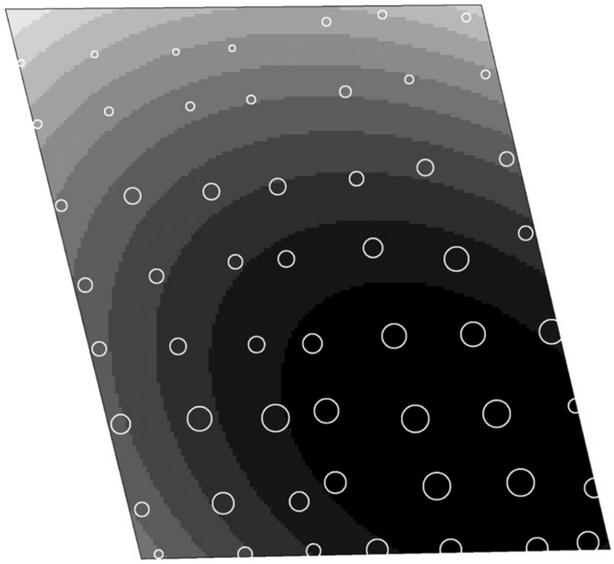

Fig. 1. Positions of the 56 sampling locations shown by the white circles, the diameters of which are proportional to the mean EC_a across all ten depths at those points. The grey layers show the horizontal quadratic trend surface fitted to those values.

therefore wish to know that the soil is effectively free of salt before they attempt to grow the crop. They want accurate estimates of the soil's salinity, both laterally from place to place within their new fields and down the profile because the rice plants are susceptible to salt in the root zone from the surface to at least 1 m. Ideally they would like three-dimensional maps of the salinity in their fields.

One can now monitor the soil's salinity using electromagnetic induction equipment such as the Geonics EM31 and EM38 instruments (McNeill, 1980). These devices measure the EC $_a$ of the soil, which is closely related to the soil's salinity. The EM38 is especially useful in that it can measure the EC_a to approximately 1.5 m depth from the surface. One can use it therefore to obtain measures of the soil's salinity throughout the root zone of the rice without having to dig or bore into the soil to take samples.

In an earlier paper (Li et al., 2013) we described the Tikhonov regularization for converting the instrumental responses of the EM38 to EC_a at ten depths in the soil in a 2.2-ha field that had been empoldered in 1996. We then modelled the three-dimensional variation in EC_a as a series of correlated two-dimensional regionalized variables, one variable for each of the ten depths down to 1.1 m, and kriged the EC_a on a fine grid at those depths. We displayed the kriged predictions as a series of maps of EC, and built from the bottom upwards a three-dimensional block diagram. Since measurements from different depths were treated as different variables, discontinuities were evident in the predicted vertical profiles and EC_a could not be predicted at depths where it was not measured.

The results revealed a trend in salinity across the field. In a second paper (Li et al., 2015), for which we had many more measurements in the topsoil, we were able to treat the data as the outcome of a linear mixed model (LMM) comprising both a fixed effect of the trend and a random residual from it and to estimate the parameters of the model by residual maximum likelihood (REML). Then by universal kriging we predicted the salinity at the nodes of a fine grid for mapping.

Fig. 7 of the paper by Li et al. (2013) also showed what appeared to be a general increase in salinity with increasing depth. In an independent study in an adjacent field the authors found that in five of the nine profiles they measured there was indeed a steady increase in conductivity.

Our aim now is to model the full three-dimensional variation in salinity, taking into account both the lateral and vertical trends, and to use whatever models we fit to predict the salinity in the three dimensions by kriging.

3. The data

The field has an area of approximately 2.2 ha. The electrical conductivity of soil, recorded as EC_a, was measured with a Geonics EM38 conductivity meter at 56 nodes, approximately on a 20 m × 20 m grid (Fig. 1).

At each position, the readings were made using EM38 instruments with the coil configured both horizontally and vertically. The first EC_a measurements were made on the ground surface to provide values of the soils EC_a to theoretical depths of 0.75 and 1.5 m, respectively. Then, the EM38 instrument was raised in increments of 0.1 m and readings were taken up to 0.6 m. Further readings were taken at heights of 0.75, 0.9, 1.1, 1.2 and 1.5 m above the surface. The linear model described by Borchers et al. (1997) was applied to this set of measurements to estimate EC_a at ten depths, namely 0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.675, 0.825, 0.95 and 1.05 m, by second-order Tikhonov regularization. The diameters of the white circles in Fig. 1 are proportional to the mean EC_a across all ten depths. These values of EC_a and their spatial coordinates comprise the data for our study. We use the following notation in referring them.

We denote by the vector $\mathbf{z}$ of length n the full set of $n = 560$ observations from $n_s = 56$ sites at $n_d = 10$ depths. We denote the spatial coordinates at which the observations were made by $\mathbf{x} \equiv \{x, y, d\}$ in which x and y are the two lateral dimensions and d is depth.

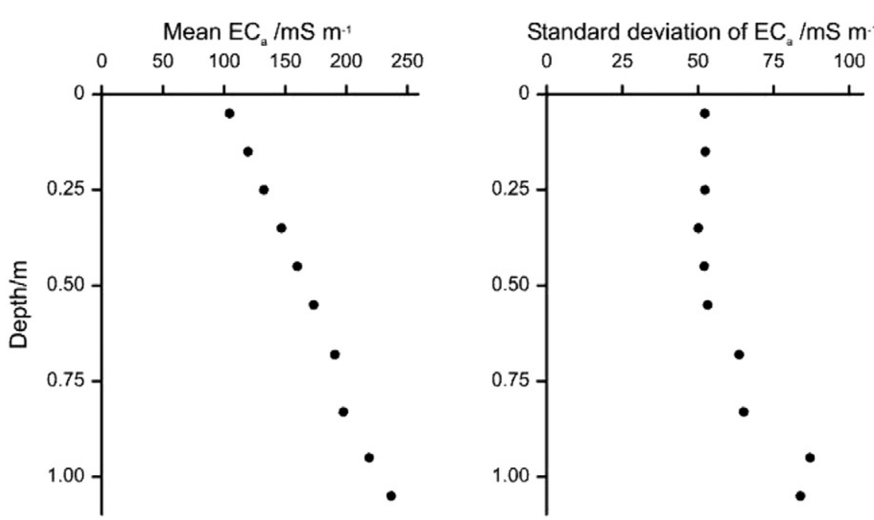

Fig. 2. (a) Mean EC_a plotted against depth; (b) standard deviation of ECa plotted against depth.