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Editors

Proximal Soil Sensing

Springer

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Foreword

Proximal Soil Sensing: Looking, Touching, Feeling

Proximal sensing is the oldest activity in soil science and forms the very core of our professional existence as soil scientists. The first soil scientists looked at what everybody called just soil and – even though others had seen before what they were seeing – they, for the first time, became really excited and recognised the unique character of what their eyes revealed. The soil as a natural body was born.

To better understand and interpret what they were seeing, they used looking glasses to magnify the soil image and smelled, tasted, and squeezed the soil material to get a better idea about its features. They also learned the hard way that soil features could be exposed only by digging pits. This elementary proximal sensing resulted in flowery analogies – such as the assertion I recall from my field training as a student that 'the feel of a loess soil was supposed to be comparable to that of the skin of an 18-year-old girl'.

Thus, at least four elementary forms of proximal sensing have been with us since the 19th century. This book convincingly illustrates that by now, thanks to modern technology, our sensing abilities reach way beyond what our human senses can accomplish. Some of these techniques have already been applied for decades in remote sensing from aeroplanes or satellites and have made significant contributions to soil and landscape science. But proximal sensing, as covered in this book, represents a special 'niche' as it defines tools that are available for field scientists who follow their own intuition and game plan as they move around in the field trying to unravel the secrets of Mother Earth, independent of a rigid flight plan or a satellite passover.

Fascinating new opportunities arise and are covered in this book: for instance, soil spectroscopy and hyperspectral sensing allow direct estimates of nitrogen, carbon, and the micronutrient contents of soil materials – in contrast to cumbersome and costly treatments associated with traditional wet chemistry. Electromagnetic induction and resistivity measurements allow a complete characterisation of soil layering, in stark contrast with traditional approaches where separate, isolated borings had to be somehow interpolated to form meaningful patterns.

At least two major advantages of proximal sensing stand out, while there are also some potential pitfalls. A major advantage is the fact that, finally, there can be enough soil data to allow meaningful (geo)statistical analyses to ascertain spatial soil patterns. So far, major advances have been made in the theory of spatial analysis (as reported in this book), but practical application has often stalled because of lack of data as research projects did not provide funds to allow adequate sampling. A second advantage is the fact that soil scientists, using these techniques, increase their scientific fecundity, which make them more effective and interesting as partners in interdisciplinary land use programs. With easily accessible soil databases, user-friendly simulation models, and flashy geographical information systems, non-soil scientists can produce many soil-related products that may look attractive at first sight but often lack depth and scope. As is true in any science, soil scientists must stay ahead in their game, and the proximal sensing toolkit is of major assistance here.

There may be a potential problem, however, if techniques start to have a life of their own and when they become a goal in themselves rather than a means towards a broader purpose, which is the dynamic characterisation of soils for the benefit of all. That is why it would be wise for modern soil scientists with their sophisticated toolkits to recall and be inspired by the initial excitement of the first soil scientists, because even though we know a lot more about our soils now, its complexity and beauty are still way beyond our understanding.

The Netherlands Johan Bouma

Preface

Our scientific understanding of soil – its unique qualities and functions – has been gained through long and arduous soil surveys complemented by careful chemical, physical, mineralogical, and biological laboratory analysis. These conventional methodologies continue to serve us well, but they can be expensive, complex, and time consuming and often only qualitative. The growing demand for good quality, inexpensive soil information underlines these shortcomings.

We need better information to solve pressing problems such as how to monitor the effects of climate change on soil, how to populate models of key processes, how to use precision agriculture for improving the sustainability and efficiency of food production, and how to assess and remediate contaminated land. These applications have prompted the development of more time- and cost-efficient quantitative approaches to soil analysis that complement, or replace, the more conventional laboratory techniques.

Sensors are becoming smaller, faster, more accurate, more energy efficient, wireless, and more intelligent. Many such devices can be used for proximal soil sensing (PSS), for example using ion-sensitive field effect transistors to measure soil pH and soil nutrients or using portable near-infrared spectrometers to measure soil properties like organic carbon content and mineral composition.

In this book, PSS is defined as the use of field-based sensors to collect soil information from close by (say within 2 m), or within, the soil body. Proximal soil sensors may be active or passive; they may be invasive, where there is direct sensor-to-soil contact, or non-invasive, measuring properties of the soil from above the surface. They may either measure the soil property directly or indirectly – by finding a proxy that is easier and cheaper to measure and developing a pedotransfer function. Frequently, the sensors are mounted on vehicles for on-the-go measurements. The rationale for PSS is that although it may produce results that are not as accurate – per individual measurement – as conventional laboratory analysis, it facilitates the generation of larger amounts of (spatial) data using cheaper, simpler, and less laborious techniques which, as an ensemble, may be highly informative. Moreover, the information is produced in a timely manner (that is, almost instantaneously).

This book reports on developments in PSS and high-resolution digital soil mapping presented at the First Global Workshop on High Resolution Digital Soil Sensing and Mapping held in Sydney in 2008. The workshop was held under the auspices of the International Union of Soil Sciences (IUSS) and was hosted by the University of Sydney Faculty of Agriculture, Food and Natural Resources, with support from the Commonwealth Scientific Industrial Research Organisation (CSIRO) and Environmental Earth Sciences International (EESI Pty Ltd). The workshop attracted 90 soil scientists, agronomists, agricultural engineers, spectroscopists, statisticians, geostatisticians, and proximal and remote sensing specialists from 18 countries.

We have selected 36 chapters, arranged in sections, which represent the range of presentations made on various aspects of PSS. The book comprises an introductory section that sets the scene; a section on soil sensing and soil sampling; a section on soil (UV), visible, and infrared spectral sensing; one on soil electromagnetic induction and electrical resistivity sensing; one on radar and gamma radiometric sensing; one on multisensor systems and other sensors; and a final section on applications of PSS.

Australia

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Part I
Overview

Chapter 1
Sampling for High-Resolution Soil Mapping

J.J. de Gruijter, A.B. McBratney, and J. Taylor

Abstract When doing sensing for high-resolution soil mapping, one has to decide on the disposition of the sensor, which is a special case of spatial sampling. To optimise the pattern of measurements, a cost model and a quality model are proposed. The quality model reflects the coverage of the geographic space, and this is illustrated with some practical experiments. Optimisation of sensing patterns is worked out for two different types of sensing equipment. If the sensor variable differs from the target (management or decision) variable, then a model is needed to predict the target variable from the ancillary data. So in that case, one also has to decide how and where to sample for calibration data. This 'calibration sampling' differs from 'sensor sampling', as now coverage of the predictor space rather than the geographic space is important. In addition, the handling of extremes is an issue here. Existing methods for calibration sampling are reviewed and a suggestion is made for a new approach, based on fuzzy cluster analysis, which might avoid some of the shortcomings of existing methods.

Keywords Soil sampling · Calibration · Proximal sensing · Latin hypercube sampling · Fuzzy *k*-means · Cost modeling

1.1 Introduction

High-resolution soil mapping often needs some form of proximal sensing, and it should be realised that this is not complete enumeration. Proximal sensing enables measurement at high densities, but practical and financial constraints usually prevent sensing at sufficiently high resolution. Thus empty spaces will remain between the sensing locations, and proximal sensing can be seen as a form of soil sampling.

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Sampling for high-resolution soil mapping therefore will often be twofold: sensor sampling and calibration sampling. Sensor sampling is in order if

- the available prior information (detailed soil maps, soil sample data, remote sensing images, previous proximal sensing data, yield data, DEMs) is insufficient for the required mapping and
- sensing can produce data about the target variable, either directly (e.g. pH sensing) or indirectly via a model (e.g. lime requirement sensing).

Calibration sampling should be done if

- a model is needed for prediction of the target variable from the prior information and/or newly acquired sensing data and
- such a model is not yet available.

The flow diagram of Fig. 1.1 shows the various possibilities of data needs and their consequences for data acquisition.

Usually one has to decide on two different spatial sampling patterns: one for the sensing locations and one for the locations from which calibration data are to be collected. It should be realised that entirely different aims are involved, leading to different methods. The aim of sensor sampling is to enable mapping so that the pattern should have sufficient coverage of the geographic space. The aim of calibration sampling is to identify a useful model so that the pattern should have sufficient coverage of the predictor space.

Like the sampling itself, the aim of this chapter is twofold. Firstly, a reconnaissance of the problems of sensor sampling is aimed at, with a first attempt to optimise sensing patterns theoretically, supplemented with some field experiments. Secondly, we shall consider some existing and possible methods for calibration sampling, which will have mostly the character of a review on the basis of a priori considerations.

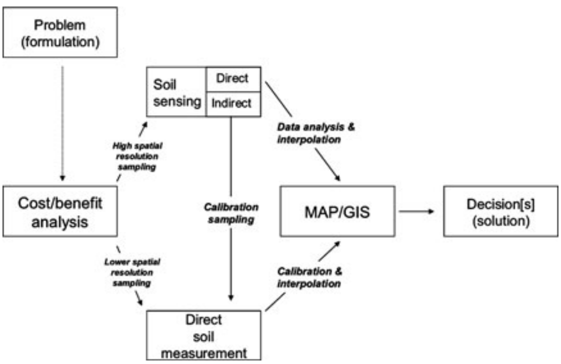

Fig. 1.1 Flow diagram of high-resolution digital soil sensing and mapping

1.2 Materials and Methods

1.2.1 Sensor Sampling: Some Theory

Sensor sampling will normally be done with a vehicle taking measurements at fixed intervals while driving along straight parallel lines, thus forming a regular grid of sample points. The size and the shape of this grid should be chosen such that the resulting sensing data will form the best starting point for interpolation onto the final grid at which the target variable is to be predicted, subject to a cost constraint. This needs a cost model and a quality model (see below). In cases where there is more than one sensor mounted on the vehicle, the measurements are generally not collocated, but we assume that the data will be transformed into collocated ones by post-processing.

For cost modelling and optimisation, we distinguish two types of equipments: sensors mounted on a vehicle that stops to take a measurement (type A) and sensors mounted on a vehicle that does not stop for measuring (type B). With type A we assume that the operator can choose the swathe width and the interval between measurements along the driving lines. With type B we assume that the measurement frequency is fixed and that the operator can choose the swathe width and the speed.

1.2.1.1 Optimisation for Equipment Type A

Assuming that we drive a sensing instrument along parallel lines through the field, with equal distance w between the lines and equal distance between sensing points h at the lines, a simple model of the variable costs is

$$C = \frac{c_{\mathrm{d}}}{w} + \frac{c_{\mathrm{m}}}{wh}, \tag{1.1}$$

where C is the variable sensing cost per hectare (€ ha^{-1}), c_{d} is the cost of driving per hectometre (€ hm^{-1}) and c_{m} is the cost of measuring per sensing point (w and h both given in hectometre). This model neglects boundary effects and driving between lines, which seems reasonable for large fields.

The patterns of sensing points that are best for spatial prediction, regardless of costs, are square grids, i.e. $w = h$. (Theoretically, triangular grids would be slightly more efficient, but these are not practical for routine application.) When we take costs into account, the optimal grid shape may be rectangular instead of square. To maximise the quality of the pattern, given a budget, we need a quality measure. Ideally we would define this in terms of prediction error variance, but that assumes that we have an explicit model of the spatial variation and knowledge of the relation between the sensor variable(s) and the target variable. In the absence of these, we can take recourse to a geometric measure that penalises large distances from prediction points to nearest sensing points. One such measure is the mean of the squared shortest distances (MSSD) of the prediction points to the sensing points (Brus et al., 2003; de Gruijter et al., 2006, p. 153). If we take this as the quality measure, Q (ha), then the model is, by double integration of the squared distance between points over a rectangle

$$Q = \frac{w^2 + h^2}{12}. \tag{1.2}$$

Using Eqs. (1.1) and (1.2) one can minimise the costs under the constraint of a given quality requirement Q_r. It can be shown by the Lagrange multiplier technique that the optimal value of h equals [for non-negative D and $(R - \sqrt{D})$]

$$h = \sqrt[3]{R + \sqrt{D}} + \sqrt[3]{R - \sqrt{D}} - \frac{2}{3}r, \tag{1.3}$$

where $r = \frac{c_m}{c_d}$, $R = 6Q_r r - \left(\frac{2}{3}r\right)^3$ and $D = R^2 - \left(\frac{2}{3}r\right)^6$.

The optimal value of w follows by substitution in Eq. (1.2). Given the cost ratio r, the optimised spacing between driving lines is a function of the quality requirement. Graphs of this function are given in Fig. 1.2 for $r = 0.05$, 0.25 and 0.5 hm.

Note that for a given cost ratio r, the ratio of the two optimal spacings h/w is a function of the quality requirement Q_r. This function is given in Fig. 1.3 for $r = 0.05$, 0.25 and 0.5 hm. The graphs show that the stronger the quality requirement, the more the optimised grid shape approaches $h/w = 1$, i.e. the ideal of the square. As expected, the rectangles of the optimised grids become more elongated as the ratio of measuring cost and driving cost is smaller.

Two extremes in terms of the cost ratio r deserve special attention. One extreme occurs when the cost of measuring is negligible; then $r \approx 0$, and according to Eq. (1.3), also $h \approx 0$. This would mean that sensing is done at the smallest possible spacing along the driving lines, the latter being $w = \sqrt{12Q_r}$ hm apart. One

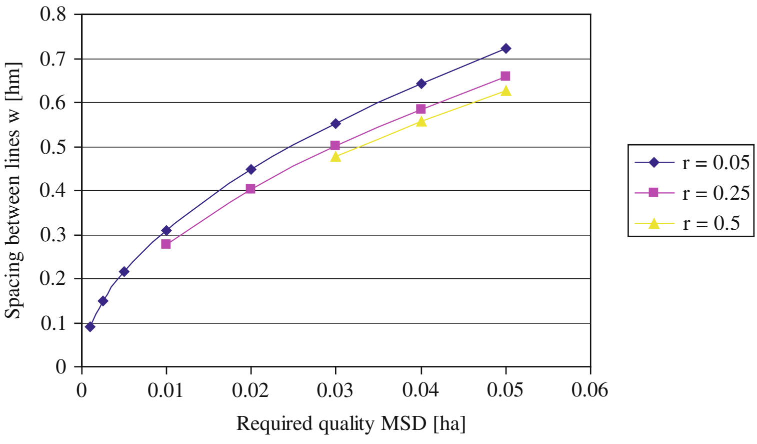

Fig. 1.2 Optimised spacing between driving lines w as a function of the required grid quality (MSSD), for cost ratios $r = 0.05$, 0.25 and 0.5 hm

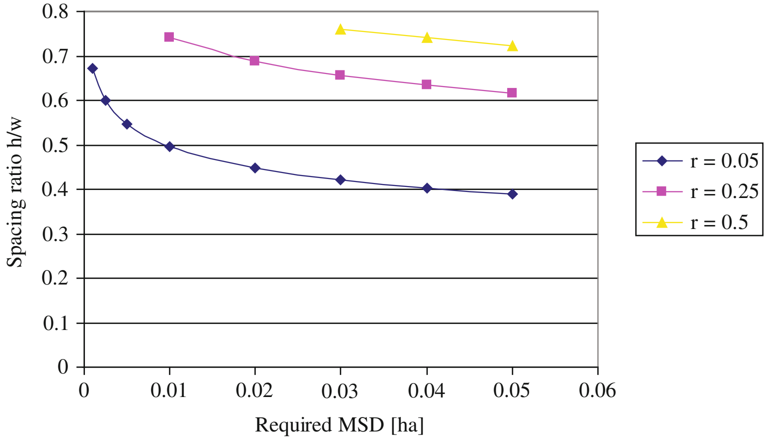

Fig. 1.3 Ratio of optimised spacings h and w as a function of the required grid quality (MSSD), for cost ratios $r = 0.05$, 0.25 and 0.5 hm

may ask if in such cases more efficient patterns can be formed by two perpendicular sets of equidistant parallel lines. The answer is negative because, to keep the investment at the same level, the spacing between the lines should be doubled and it can be shown that Q would then equal approximately $w^2/9$ instead of $w^2/12$.

The other extreme is when the cost of driving is negligible compared with measuring. The only concern is then to keep the sensing density as low as possible, under the constraint Q_r. The optimal grid shape is now square for any density so that [from Eq. (1.2)] $h = w = \sqrt{6Q_\mathrm{r}}$.

The spacing between the lines cannot always be chosen freely because there may be controlled driving lines in the field, say w_m apart. In that case w is allowed to take only the values w_m or multiples of it. Given Q_r and a series of permissible values of w, optimisation can be done by calculating h from Eq. (1.2) and C from Eq. (1.1) for each value of w and selecting the (w, h) combination with the smallest C.

1.2.1.2 Optimisation for Equipment Type B

Assume that we drive the vehicle at speed v (m min^{-1}) while the sensor is measuring at frequency f (min^{-1}). A cost model in terms of time T (min ha^{-1}) needed for optimisation is now as follows:

$$T = \frac{1}{w \cdot v}. \tag{1.4}$$

The measuring interval along the lines h is determined by speed and frequency: $h = v/f$.

Minimising T, again under quality constraint Q_r, results in $w = h = \sqrt{6Q_\mathrm{r}}$. So with this type of equipment one should always strive for a square grid, regardless of the quality requirement and the measuring frequency, as with type A when driving costs are negligible.

1.2.2 Sensor Sampling: Some Experiments

Three surveys were done in a 9.4-ha field located at ‘The Lagoon’ near Bathurst, New South Wales, on the flood plain of the Campbell River. Soil ranged from sandy, crusting, coarse textured profiles (Arenosols) with rock fragments on the higher elevations to heavy alluvial clays (Fluvisols) on the flats adjoining the river. The surveys were done with equipment of type B (non-stop driving) with an EM38 (horizontal): (1) fast driving in north–south direction; (2) slowly driving in north–south direction, half the speed but double swathe width of (1); and (3) same as (2) but in east–west direction. The driving lines were approximately straight, parallel and equidistant, two times farther apart with the slow surveys than with the fast one (13.3, 26.6 and 26.8 m on average). Figure 1.4 shows the swathe patterns for the three surveys.

The difference in speed caused differences in spacing between the measurements along the lines. The variable costs of the three surveys were approximately equal. See Table 1.1 for the key parameter values of the surveys. The numbers in brackets in this table are the expected parameter values after optimisation of the sampling design, given the same measuring frequencies and quality requirements as realised in the surveys.

The EC_a was mapped by ordinary kriging with the three datasets separately, and the mean kriging standard deviation was calculated. Figure 1.5 shows that, as expected, both the geographic pattern quality and the geostatistical pattern quality are better for the fast survey than for the slow survey, because the grid pattern is less elongated. This better quality was achieved with no extra costs.

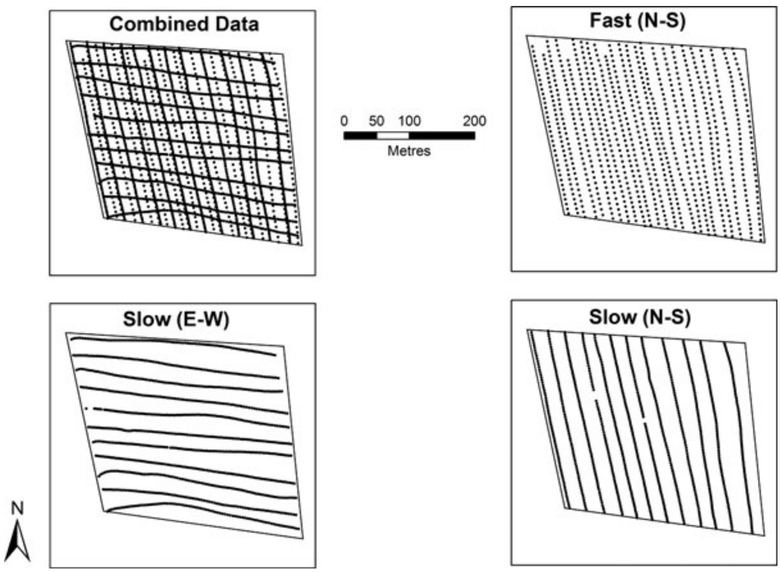

Fig. 1.4 Swathe patterns as applied in three sensing experiments

Table 1.1 Key parameter values of the three surveys

Survey parameter	Fast N–S	Slow N–S	Slow E–W
Swathe width, w (m)	13.3 (11.0)	26.6 (19.0)	26.8 (19.0)
Sample size, n	870	965	1035
Total line length (m)	7,080	3,540	3,520
Interval, h (m)	8.14 (11.0)	3.67 (19.0)	3.40 (19.0)
Frequency, f (min^{-1})	24.2	24.7	28.8
Speed, v (m min^{-1})	197 (267)	90.8 (469)	97.8 (547)
Time, T (min ha^{-1})	3.82 (3.40)	4.13 (1.12)	3.82 (0.96)
Quality, Q (m^2)	20.3	60.1	60.8

Values for the optimised pattern are represented in brackets, given the same frequency and quality requirement as realised in the survey

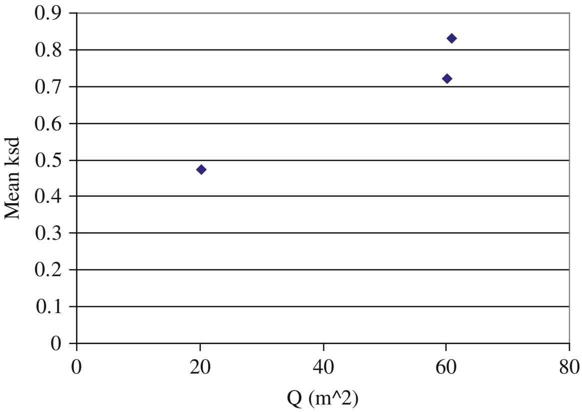

Fig. 1.5 Geometric pattern quality Q (Eq. 1.2) versus geostatistical pattern quality (mean kriging standard deviation) for the surveys fast N−S, slow N−S and slow E−W (from left to right)

Table 1.1 shows that optimising the sensing pattern at the low-quality level of the slow speed surveys would decrease the survey time by about 75%. However, this could be achieved only with a more than four times higher speed of driving, which is clearly impracticable. Optimising the sensing pattern at the higher quality level of the fast survey decreases the survey time much less than with the slow surveys (11%), and this would require a 36% higher driving speed. However, as the speed of the fast survey was already high from the point of view of sensing precision, such a speed-up might be at the cost of too much loss of data quality.

1.2.3 Calibration Sampling

As opposed to sensor sampling, in calibration sampling, aliquots are taken to the laboratory for measurements, and the total costs are therefore dominated by the