Non-intrusive sensors for measuring soil physical properties

PMR DAMPNEY[1], JA KING[1], RM LARK[2], HC WHEELER[2], RI BRADLEY[3], TR MAYR[3]

[1]ADAS Boxworth, Cambridge CB3 8NN
[2]Silsoe Research Institute, Wrest Park, Silsoe, Bedfordshire, MK45 4HS
[3]National Soil Resources Institute, Cranfield Univ., Silsoe, Bedfordshire, MK45 4DT

Summary

Various remote sensing technologies might be used in arable agriculture to help improve soil and nutrient management. Potential techniques are Electro Magnetic Induction (EMI), Ground Penetrating Radar (GPR) and Spectral Reflectance. Research has shown that EMI sensing can be operated simply and easily and can provide useful and practically relevant information but will not fully substitute for field inspection of soil properties (i.e. by soil auger or spade). GPR sensing is a complex technique and not currently sufficiently developed for practical use in agriculture. Spectral reflectance of bare soils can be useful to detect contrasting soil surface colours (e.g. organic matter differences), but is more useful for detecting patterns in growing crops which may, or may not, reflect differences in the nature of the underlying soil.

Introduction

Knowledge of the physical make-up of soils has always been important for farmers when making decisions concerning crop management inputs such as lime and fertiliser, cultivation and sub-soiling/drainage. More precise soil knowledge, including information on boundaries between soil types, should result in more accurate use of fertilisers and agro-chemicals. The introduction of precision farming techniques (*e.g.* GPS, yield mapping, machinery capable of variable rate application, sensors) has encouraged farmers to pay more attention to crop variations that exist within a farm and within individual fields. Recent research has confirmed that variation in crop yields is primarily due to variations in soil type, and that knowledge of soil types and the location of boundaries between them is essential if these technologies are to realise their potential. The key soil physical properties that are important for cropping and husbandry decisions are soil texture, depth to bedrock, wetness and organic matter; information on soil nutrient levels is important for lime and fertiliser decisions. A major problem is that current methods for obtaining information on soil physical properties are manual and often require the input of a specialist soils adviser. Even with such input, small-scale variations can be missed unless very intensive (and therefore expensive) soil survey methods are used.

A recently-completed HGCA-funded project (King *et al.,* 2003) has studied the use of soil sensors for gathering information on soil physical properties. This paper takes account of the results and conclusions of this study.

Sensing using Electro Magnetic Induction (EMI)

In recent years the technique of measuring the electrical properties of soil has emerged as a potential tool to help differentiate and map various soil variables (King & Dampney, 1999). Measuring the electrical conductivity of soil/water paste extracts has long been used in arid climates to evaluate the soil solute concentration when assessing a soil salinity hazard. Typical electrical conductivity (EC) values for some soil components are shown in Table 1.

Table 1. Typical ranges of electrical conductivity (Kollert, 1969).

Material	**EC (mS/m)**
Irrigation water (0.7% salt)	<1500
Potable water (0.25% salt)	<550
Clay	10-1000
Sand	0.01-1
Loam	20-200
Topsoil	5-20
Sandstone	0.1-50
Limestone	0.4-20
Crystalline rocks	<0.001-1

The electrical current needed to measure soil conductivity can be induced using electrodes inserted into the soil, or electro-magnetically using principles similar to those in operation in electrical transformers (McNeill, 1980). In the EMI technique, a transmitting coil is energised with an alternating current and placed on the soil surface. This sets up a magnetic field that induces a weak electrical current in the soil, which in turn generates a magnetic field in a second receiving coil a set distance from the transmitting coil. This generates a direct current proportional with that in the transmitting coil, but altered by the electrical conductivity of the soil. The apparent electrical conductivity (EC_a) is linearly proportional to the ratio of the two magnetic fields. The electrical coils used can be suspended a few centimetres above the soil surface. Using a 1m inter-coil spacing, the zone of influence can be a soil depth of 1.5 to 3.0m.

From Table 1, it can be seen how the EC_a is likely to be influenced by soil texture, moisture content and solute concentrations within the zone of influence. Therefore, some knowledge of the site will always be needed to explain the soil factors that are having influence on the readings. Nevertheless, this opens up the possibility of mapping the EC_a of a field to contribute to a more accurate and cost-effective mapping of soil types.

The EMI instrument can be used in two modes, with the coils either vertically or horizontally orientated. With the coils in a vertical orientation, the signal obtained may be influenced by soil material within a 4m depth, but the upper 1.5m of soil contributes most. In horizontal mode, the signal interacts with a shallower soil depth (<2m), but is more strongly influenced by the upper 50cm.

In the HGCA project, 4 fields of contrasting soil types were mapped for EC_a using an ATV-drawn cart containing an EMI sensor, with a GPS kit to locate the equipment within each field (Figure 1). Mapping was carried out at 6m intervals in both winter (wet soil conditions) and summer (dry soil conditions). For each field, an independent pedological soil survey was carried out. Topsoil and subsoil characteristics were described approximately every 1ha and along fixed transects, and soil samples taken for laboratory analysis - clay%, sand%, organic carbon% (OC) and bulk density (BD) in both topsoil and subsoil. Available water (AW) contents were calculated using pedo-transfer functions (Mayr *et al.*, 1999). In each field, past yield data was also analysed and classified using the technique of Lark *et al.* (2003) as a means of mapping field areas that have similar yield patterns over several years.

Figure 1. EMI equipment in cart drawn by an ATV.

Table 2 summarises the regression statistics and data for the comparison of yield class means and EC_a. For each field, the EC_a data detected significant differences in at least some soil properties. In some cases (e.g. field 1B, field 3), the yield classification was more closely related to subsoil rather than topsoil properties compared to the EC_a data. This might be expected as yield will tend to integrate the effect of soil properties throughout the rooting depth of the crop that can be over 1m, whereas the EMI technique will interact with soil independently of the growing crop. Comparing the residual variances over all fields shows that neither yield maps nor EC_a were consistently more useful for predicting soil physical properties.

EC_a was regressed on the principal components for the combined data set from 3 sites Since the principal components were not correlated, those which made a significant contribution to explaining variation in EC_a (PC1>PC6>PC2>PC8) could be identified. PC1, PC2 and PC8 were negatively correlated with EC_a values, whilst PC6 was positively correlated. Figure 2 shows the weighting of the original soil variables in these four components. The large circular symbols indicate where large EC_a values are expected in the plot and the small circular symbols show where small EC_a values are expected. Hence high clay contents and bulk densities in both topsoil and subsoil are associated with high EC_a values. Topsoils and subsoils with a high sand content, and subsoils with a high organic carbon content were associated with low values of EC_a. From all correlations, the following significant relationships were found:-

- topsoil clay%, topsoil sand% ($p<0.001$); topsoil organic carbon% ($p<0.01$)
- subsoil clay%, subsoil sand% ($p<0.01$); subsoil AW, profile AW ($p<0.05$)

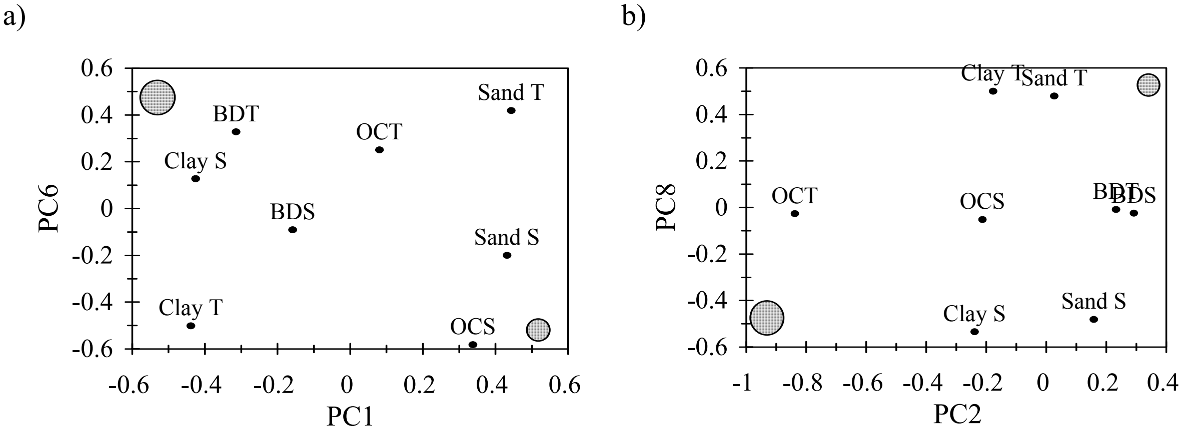

Figure 2. Elements for the latent vectors for PC1 and PC6 (a) and PC2 and PC8 (b) of static soil properties in combined datasets from three sites (T=topsoil, S=subsoil, BD=bulk density, OC=organic C).

Figure 3 shows maps from one site where soils vary from deep sandy to deep clayey (field 3). Cluster analysis of yield maps identified 4 class centres (Figure 3a) which were distributed across the field as shown in Figure 3b. Regression modelling of soil properties (Table 2) showed that the subsoil clay content and subsoil sand content were significantly related to the class of maximum membership. This might be expected as these soil properties have a major influence on crop yield due to variations in soil AW. Yields were highest in class 4 - the subsoil in sub-regions of this class had a high clay% and low sand%. In areas of low yielding class 1, the subsoil had a low clay% and high sand%. There were no significant relationships with the other measured soil properties.

Figure 3c shows the map of soil EC_a which shows a strong resemblance to the yield class map. Regression modelling (Table 2) showed that EC_a was strongly related to topsoil clay and sand but also related to some degree to most other measured soil physical properties in both topsoil and subsoil.

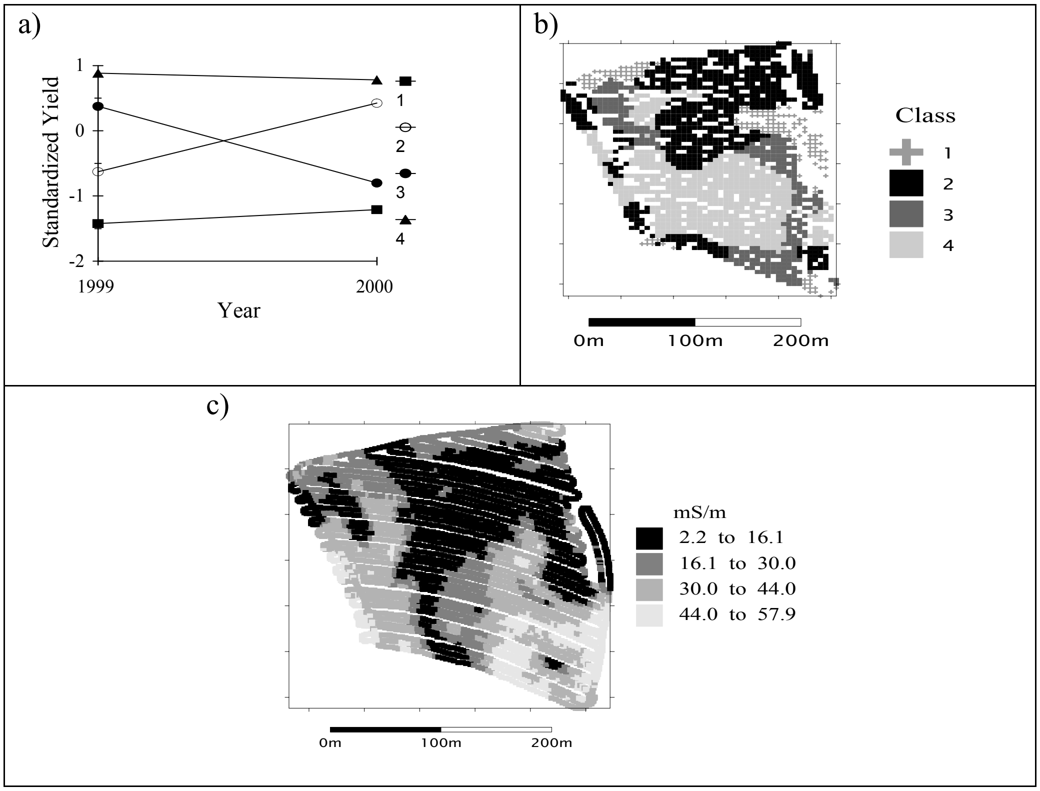

Figure 3. Class centres (a), class of maximum membership (b) and soil EC_a (c) in field 3.

Multivariate spatial and cluster analysis was used in order to assess the stability of EC_a patterns with time. Although the absolute values of soil EC_a changed significantly according to the prevailing soil moisture levels at the time of measurement, kriged estimates of the change in EC_a showed that the spatial patterns of EC_a were generally stable for all fields studied, irrespective of whether the measurements were undertaken under moist (over winter) or dry (summer/autumn) soil conditions.

Practically, the over-winter period, when soils are at field capacity but not waterlogged, would seem a sensible time to take EMI measurements. EMI equipment can be operated quickly and relatively cheaply. Travel at speeds of 10-20km per hour is realistic but the equipment should not be allowed to ‘bounce’ over excessively bumpy ground. Geostatistical analysis of EC_a data from 9 separate datasets (Table 3) showed that, to obtain point predictions of EC_a with an error of less than 10%, a pass spacing of <5m was usually needed. However, spacings of around 20-25m commonly gave point predictions with errors of less than 25% that King *et al.* (2001) considered to be an acceptable compromise for practical purposes. However, to obtain an estimation error of <10% between 10m square blocks commonly required a pass spacing of only 10–20m.

Table 3. Pass spacings required for an error of <10% of the mean (<25% in brackets).

Point Kriging	Block Kriging (10m block)
19	42
<5 (16)	11
<5 (20)	12
<5 (24)	11
<5 (17)	11
<5 (24)	13
<5 (>60)	32
<5 (44)	17
14	21

Sensing using Ground Penetrating Radar (GPR)

GPR is a time-domain impulse radar that transmits broad bandwidth pulses into geologic media, and acts as a sounding device very much like depth finders in boats. The system consists of an antenna (transducer), that acts as both a transmitter and receiver of radar pulses, a recording/control unit, which can display real-time image of what the device has "seen", and connecting cables. GPR is a reflection system that uses non-ionizing electromagnetic waves to probe the material under investigation, picking up echoes that bounce back from the objects or interfaces within the material.

The potential of GPR is severely limited by the nature of the soil material in a field. On clayey soils, it is usually difficult or impossible to obtain any readings as effectively the signal is reflected by the extreme soil surface and does not penetrate to any useful depth. On sandy soils, some useful information can be obtained on the location of bedrock or free-water interfaces in the profile. In contrast to the EMI technique, GPR has the potential to indicate the soil depth at which a feature occurs (e.g. a rock layer). However, the operation of GPR sensing is slow, the interpretation of the output is not easily automated. Overall, the technique is not currently sufficiently developed for practical use in agriculture.

Sensing using Spectral Reflectance

Sensing by reflectance of electromagnetic radiation at certain wavebands has found most application in monitoring vegetation and crop cover. This application has already been reviewed for MAFF (Dampney *et al.*, 1998). Commonly, measurement of specific crop characteristics involve the use of some form of Vegetation Index, the simplest of which is a ratio of “near infrared” (750nm) to “red” (650nm) responses (Steven and Clark, 1990).

The reflectance from soil surfaces is not simply a function of the colour of the mineral particles, but depends also on their organic matter content, moisture and structure. The measurement of soil variables using spectral reflectance is likely to be restricted to those soil features that occur at or very close to the soil surface. Reflectance of incident radiation is not influenced by soil properties at depth. Practically, there is also the problem that bare soils with minimal cover of trash, commonly only occur for short periods during the year.

There is more potential for the use of spectral reflectance of cropped soils where variations in the crop can often reflect variations in the underlying soils. Either simple (e.g. aerial photographs) or sophisticated (e.g. satellite images) techniques are practically available but at differing costs. Careful interpretation of such information and verification by in-field examination is crucial when making use of any of these information sources, but they can provide a valuable source of additional information to help decision-making on crop management practices. There are substantial archives of aerial photographs and satellite images available.

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