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SHORT COMMUNICATION

Height above ground corrections of EM38 readings of soil apparent electrical conductivity

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Introduction

Knowledge on how key soil properties vary, both spatially and temporally, is important when taking management decisions in order to optimize crop growth conditions. To achieve such information, the use of sensor techniques provides a time- and cost-effective alternative to traditional soil sampling and laboratory analyses. One sensor-based, non-invasive technique is to measure apparent electrical conductivity (EC_a) of a whole soil profile by means of electromagnetic induction (EM). EM-EC_a has been used successfully as an indirect indicator of important soil physical and chemical properties, such as soil water content (Khakural et al., 1998; Sheets & Hendrickx, 1995), soil salinity (Williams & Baker, 1982), topsoil inorganic N content (Korsaeth, 2005) and nutrient levels (Heiniger et al., 2003). Whereas these studies focus mainly on soil variation in the lateral plane, others have used the EM-EC_a technique with more emphasis on the vertical soil variation, such as depth of sand deposition (Kitchen et al., 1996) and topsoil thickness (Kitchen et al., 1999).

The Geonics EM38 (Mississauga, ON, Canada; www.geonics.com) is the EM-EC_a sensor most often used in agriculture (Sudduth et al., 2001). The device has an intercoil spacing of 1 m and may be operated in one of two measurement modes. In vertical mode (coil axes perpendicular to soil surface, EM_V) the effective measuring depth is approximately 1.5 m, whereas in horizontal mode (coil axes parallel to soil surface, EM_H) the effective measuring depth is approximately 0.75 m.

Soil mapping by means of the EM38 device is offered commercially in many countries, such as New Zealand (www.nzcpa.com), Denmark (www.gpsagro.dk), Sweden (www.analycen.se) and Norway (www.planteforsk.no). The most common way to perform the mapping in the field is to tow the instrument on a sled behind a terrain vehicle. This normally involves mounting the instrument at a certain height above the ground (e.g., Corwin & Lesch, 2003; Eigenberg et al., 2002; Kitchen et al., 2003; Sudduth et al., 2001). The measurements of EC_a with EM38 are, however, strongly affected by this height (Sudduth et al., 2001). To be able to compare measurements conducted at different heights (e.g., when different mobile constructions are used), it is of interest to find a method to correct measurements for height. The objective of this research is to find a simple but robust method to correct for the height at which the EM38-measurements were made.

Material and methods

Deriving the correction functions

Correction functions were derived from the linear model (Eqs. 1–6) of McNeil (1980). In this model, prediction of apparent conductivity-readings made with the instrument in horizontal mode (EM_H) is given by:

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$$EM_H(h) = \int_0^\infty \phi h(z+h) \quad \sigma(z)\, dz \tag{1}$$

where h is the height of the instrument above the ground and $\sigma(z)$ gives the conductivity at depth z (depth as positive direction). The sensitivity function $\phi_H(z)$ is given by:

$$\phi_H(z) = 2 - \frac{4z}{(4z^2 + 1)^{1/2}} \tag{2}$$

Predictions of the apparent conductivity reading with the instrument in vertical mode (EM_V) is given by:

$$EM_V(h) = \int_0^\infty \phi v(z+h)\, \sigma(z)\, dz \tag{3}$$

where

$$\phi_v(z) = \frac{4z}{(4z^2 + 1)^{3/2}} \tag{4}$$

R(z) is the relative contribution to EM38-readings from all material below a depth z, given by integrating Equations 2 and 4, for the horizontal and vertical mode, respectively:

$$R_H(z) = \int_z^\infty \phi_H(z)\, dz = (4z^2 + 1)^{1/2} - 2z \tag{5}$$

and

$$R_V(z) = \int_z^\infty \phi_V(z)\, dz = \frac{1}{(4z^2 + 1)^{1/2}} \tag{6}$$

Since the electrical conductivity in air is practically zero, the effect of lifting the device to a height h would theoretically be the same as evaluating Equations 5 and 6 for $z = (-1)h$ (since depth is chosen as positive direction in the linear model of McNeil (1980), the height is here negative). The effect on the EM38-readings depends, however, not only on the relative weight of the signal, but also on the actual conductivity at each depth (see Equations 1 and 3). If, for simplicity, we assume that the soil profile has uniform conductivity, correction functions for measurements conducted at some height h above the ground may be established on the basis of Equations 5 and 6, for EM_H and EM_V, respectively:

$$EM_{H\ corr} = EM_H \frac{1}{(4(-h)^2 + 1)^{1/2} - 2(-h)} \tag{7}$$

$$EM_{V\ corr} = EM_V (4(-h)^2 + 1)^{1/2} \tag{8}$$

where subscript corr indicates height corrected EM38-readings.

Soils with vertical uniform conductivity are very rare in practice, and it is very unlikely that the soil at the experimental sites had such uniformity, since there was considerable variability in their properties at different depths (data not shown, see Korsaeth 2005 for details). However, detailed knowledge about soil layers and electrical conductivity profiles is seldom available, and the method was tested in spite of this obviously weakly based assumption.

Measurements

Measurements with EM38 were conducted in an ongoing field trial (Korsaeth, 2005) with alternative fertilizer applications (0, 60, 90, 120 and 150 kg N ha^{-1}) to spring barley, at two sites with morainic loam in SE Norway; Apelsvoll Research Centre (60°42′N, 10°51′E) and Kise Research Station (60°46′N, 10°48′E). Two weeks after sowing/fertilization in spring 2003 (27 May), EC_a was measured at both sites on all five treatments in three of the 20 replicate blocks on the ground and at 20, 40 and 60 cm above the soil surface. Both EM_H and EM_V were measured by operating the device manually and placing it on a specially designed wooden frame to ensure correct height at measuring. All meter readings were conducted at three points within each plot.

Data analyses and statistics

The arithmetic means of the measuring points were corrected for height by equations 7 and 8, respectively. Simple correlations were then calculated between height corrected values and the values measured at ground level for both EM_H and EM_V.

Results and discussion

Measurements of EC_a were highly affected by the height above the ground at which the EM38 was held (Figure 1), and a regression model using height as the only predictor could explain 52% (p <0.001) and 41% (p <0.001) of the overall variation in EM_H and EM_V, respectively. The height correction functions, based on the depth-related sensitivity functions of EM38, were very well suited to correct measurements conducted 20 cm above the ground, both at Apelsvoll and at Kise (Table I, Figure 1). This was in spite of the fact that the soil horizons at both Apelsvoll and Kise were far from uniform with respect to the distribution of soil organic matter, clay content and other properties that influence electrical conductivity.

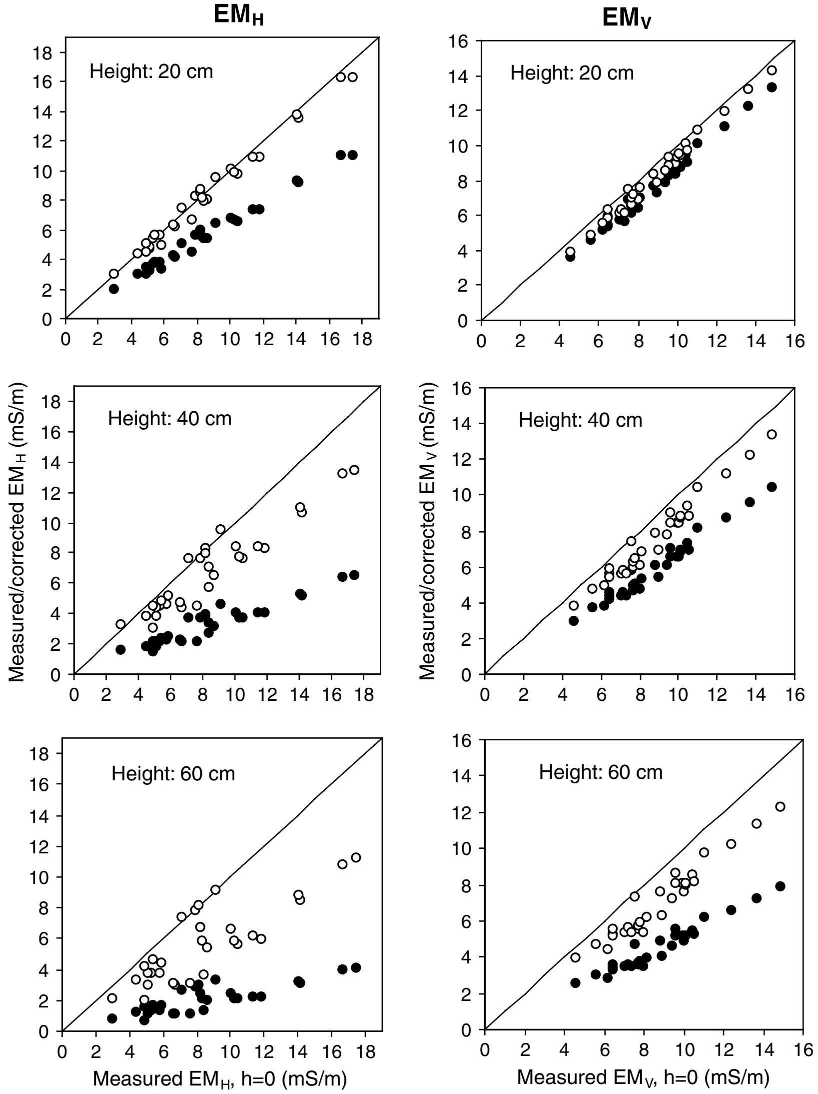

Figure 1. Apparent electrical conductivity measured with EM38 in horizontal mode (left plots) and in vertical mode (right plots) placed on the ground and at heights 20 cm (upper plots), 40 cm (middle plots) and 60 cm (lower plots) above the ground (filled circles), and height corrected measurements (open circles) calculated with Equations. 7 and 8 for EM_H and EM_V, respectively. The 1:1 lines are indicated.

Table I. Correlation coefficient between apparent soil electrical conductivity (EC_a) measured on the ground with EM38 and estimated ground values, based on measurements with EM38 at different heights using equations 7 and 8 as transfer functions for EM_H and EM_V, respectively. All correlations were significant at $p < 0.001$

	Height (cm)		
Location/mode	20	40	60
Apelsvoll ($n = 15$)			
EM_H	0.979	0.931	0.899
EM_V	0.975	0.942	0.912
Kise ($n = 15$)			
EM_H	0.997	0.986	0.975
EM_V	0.996	0.993	0.990
All data ($n = 30$)			
EM_H	0.993	0.940	0.838
EM_V	0.993	0.982	0.966

Although the height corrected EM38-readings correlated strongly ($r \geq 0.9$ in all but one case) (Table I) with the corresponding ground readings (measurements made with the device placed on the ground), for both locations and for all heights tested, there was an overall tendency that the performance of the height correction functions decreased with increasing height, as the corrected values increasingly underestimated the ground measurements (Figure 1). This was more pronounced for EM_H than for EM_V (Figure 1), and more pronounced at Apelsvoll than at Kise (Table I). Different performance between EM_H and EM_V is related to the different sensitivity functions on which the respective correction functions were based. The sensitivity function of EM_H (Equation 2), shows that the relative weight of the measured signal is largest at the soil surface, and decreases almost exponentially with depth. The sensitivity function of EM_V (Equation 4) has another shape. Here the relative weight of the signal increases from zero at the soil surface to a peak at about 40 cm depth, from where it decreases at greater depths. As a consequence, the profile heterogeneity affects the measurements of EM_H and EM_V differently with increasing measurement heights.

In conclusion, the correction functions presented offer theoretical models to correct EM38-measurements when measuring at an instrument height of 20 cm above the ground surface, a height which is within the interval of what is commonly used in practice for mobile operation of the device (e.g., Kitchen et al., 2003; Kitchen et al., 1996; Sudduth et al., 2001). The method is not yet tested for heights below 20 cm.

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