Root zone soil moisture content in a Vertosol is accurately and conveniently measured by electromagnetic induction measurements with an EM38.

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Abstract
It is sometimes preferable to measure soil moisture content without destructive sampling or equipment installed in the field (as required for TDR probes and neutron probes). Electromagnetic induction (EMI) instruments are lightweight and portable, and measure apparent soil electrical conductivity (ECa), which is affected by moisture content. The EM38 is an EMI meter that is usually used for mapping salinity. As well as salinity and soil moisture, EMI meters respond to factors including clay content, soil temperature and magnetic minerals. Assessing the importance of these factors, and negating them where possible, would be a significant step toward using EMI for routine soil moisture measurement. This study shows that EMI measurements can accurately predict soil moisture content at a range of depths.

Key Words
EM38, soil moisture, electro-magnetic induction.

Introduction
Soil moisture measurement is a key to studies of the water balance. One of many methods of measuring soil water is to induce electrical currents in the soil and measure subsequent electromagnetic emissions (current lags voltage by 90º in an inductor). EMI meters for soil have been used since the 1960s (e.g. Howell 1967), often for metal detection, archaeological surveys and salinity mapping. The EM38 (Geonics Ltd., Ontario, Canada) is a contemporary EMI meter that is easy to use, lightweight, and can be used to rapidly measure many locations without the need for in-field installations or destructive sampling. It displays units of the apparent electrical conductivity (ECa, mS/m).

Soil moisture content affects the use of the EM38 for measuring soil spatial variability to the extent that Corwin and Lesch (2005) suggest "It is important to remember that if the water content of the soil drops too low (e.g. <0.10 $cm^3\ cm^{-3}$), then the EM signal readings can become seriously dampened. In most practical applications, reliable EM signal data will be obtained when the soil is at or near field capacity. Surveying dry areas should be avoided."

ECa may be considered a function of the ECa of the soil solids (ECs, mS/m) and the soil solution (ECw, mS/m)), the soil moisture content (W, cm^3/cm^3) and a tortuosity coefficient (T) (Cook and Williams 1998, equation 1). Therefore, a curvilinear relationship might be expected between ECa and W, with an intercept of ECs.

$$\text{ECa (mS/m)} = \text{ECs} + \text{ECw.W.T} \qquad (1)$$

ECs is affected by the concentration of conductive, magnetic and dielectric materials in the soil. Buried metal, including metallic minerals, have extremely high ECa. Some soil magnetic materials possess magnetic viscosity, a transient magnetism that affects ECa. The minerals include magnetite and maghaemite. Magnetic viscosity depends mainly on the abundance, grain size distribution, and oxidation state of iron, titanium and other elements. Dielectric materials including water, organic matter and clay minerals affect ECa, but not EC, by transmitting alternating current (but not direct current). ECa also increases with temperature, by approximately 1.9% per degree C (Corwin and Lesch 2003).

If temperature is relatively constant, or accounted for, and the change in salinity is not great, a site-specific relationship between ECa and water content can be found (Akbar *et al.* 2005; Huth and Poulton 2007). The aim of this study was to measure soil moisture content and ECa in a black Vertosol (Isbell 1998). Key measures of success were the ease and quality of calibration, calibration quality at a range of soil depths, and ease of use.

Methods

Suitability of the EM38 for measuring ECa

For EMI meters to measure a signal that is proportional to the apparent conductivity of the adjacent soil, the induction number (IN) must be less than 1, and preferably less than 0.1. IN is the unitless ratio of distance (m) between the coils to the depth of conduction (m). For the soil in question and an EM38, IN is very low. It is between 0.01 to 0.10, depending on the exact electrical conductivity and magnetic permeability of the soil.

Site and measurement information

ECa (mS/m) measurements were made with an EM38 and volumetric soil moisture measurements (W, g/cm^3) were made concerning a black Vertosol (Isbell 1998) near Pampas, 35 km southwest of Toowoomba. Duplicate cores were taken for gravimetric moisture content and a single core for bulk density, in 0.2 m increments. Measurements were made at a wide range of soil moisture contents, including moist soil (near the drained upper limit) that had been bare fallowed and much drier soil under nearby woodland vegetation. The EM38 was used in vertical and horizontal modes at the soil surface and 0.1 m and 0.4 m above the soil surface. Raising the EM38 reduces the depth of soil moisture measurement (Rhoades and Corwin 1981; Cook and Walker 1992). Table 1 shows the depths considered for these combinations of modes and heights above the ground. Two EM38 meters were used for some samples to check for meter-to-meter differences.

Table 1. Depth in the soil of the nominal depth of sounding (m) in two modes and at three heights above the ground. The nominal depth of sounding includes 90% of the depth response of the EM38 at 0m.

	Height of measurement (m)		
Mode	0	0.1	0.4
Vertical	1.5	1.4	1.1
Horizontal	0.75	0.65	0.35

Linear regression was used to predict soil moisture content (mm) to a range of soil depths (m) from ECa measurements (mS/m) (Table 1).

Effects of temperature

Measurements at a nearby site showed that subsoil temperatures were near their annual maxima (24 to 26 C, depending on depth) and relatively constant. Due to this, and wishing to consider the common scenario where data for soil temperature are not available, the ECa data were not corrected for soil temperature.

Results

Differences between meters

The two meters gave similar relationships between ECa readings and soil moisture content (Figure 1). It was concluded that they are sufficiently similar for both instruments to be calibrated together.

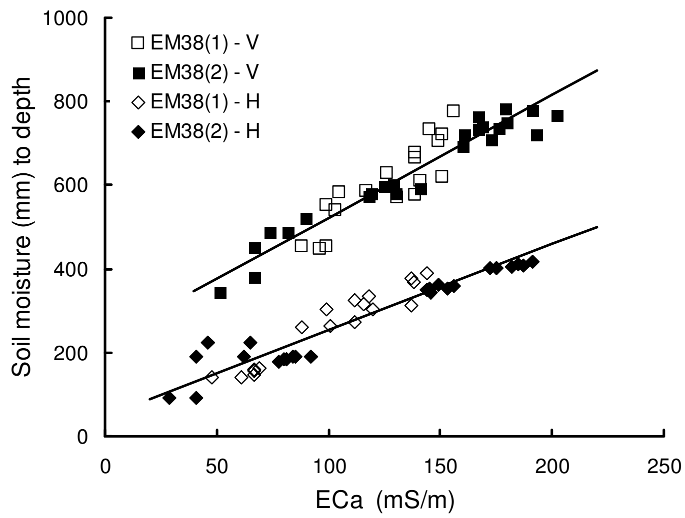

Figure 1. The calibration data from two EM38 meters (1 and 2) used in vertical (V) and horizontal (H) modes.

Relationships between ECa and soil moisture content

Figure 2 shows the relationship between ECa and soil moisture content for the EM38 used in the vertical mode. The regression data are shown in Table 2.

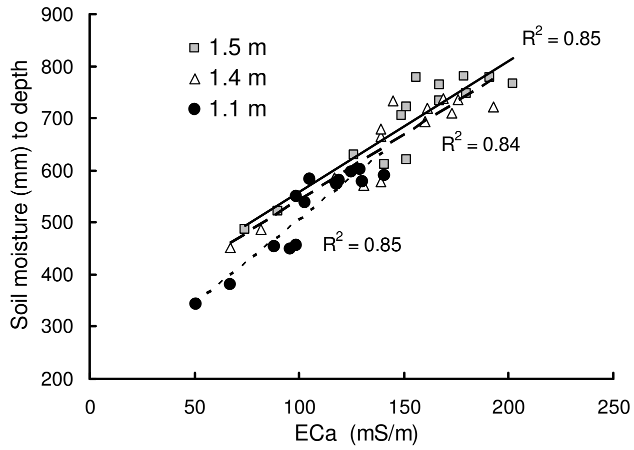

Figure 2. Soil moisture (mm) and ECa (mS/m) measured in vertical mode to 3 depths.

Figure 3 shows the relationship between ECa and soil moisture content for the EM38 used in the horizontal mode. The R^2 values are greater than for the vertical mode (see also Table 2).

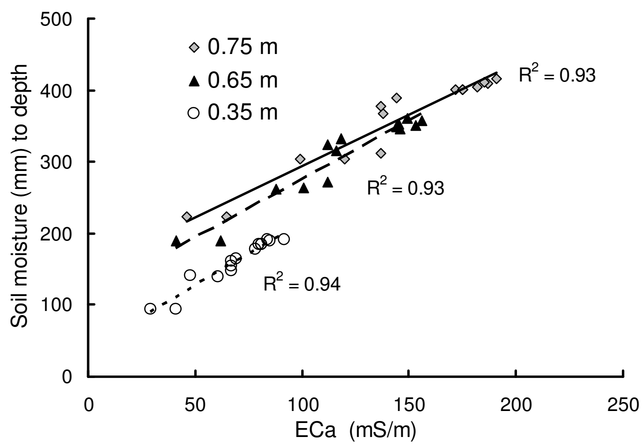

Figure 3. Soil moisture (mm) and ECa (mS/m) measured in horizontal mode to 3 depths.

Table 2. Regression coefficients and parameters for Y=a + bX, where Y is the soil moisture content (mm) and X is the ECa (mS/m), as measured by an EM38. The coefficients are not independent. SE is the standard error.

Depth (m)	a (mm)	b (mm/mS/m)	R^2	SE (mm)
0.35	38	1.77	0.94	9
0.65	113	1.63	0.93	16
0.75	152	1.42	0.93	19
1.1	183	3.22	0.85	33
1.4	292	2.50	0.84	38
1.5	307	2.52	0.84	39

Conclusions

Our principal finding is that the factors that might potentially blur the relationship between ECa and soil moisture content had only minor effects. These factors include air temperature, soil temperature and spatial variability in conductivity due to clay, salt and magnetic mineral content. The meter response appears linear over a wide range of soil moisture values, as verified by the high R^2 values in Figures 2 and 3. The response in vertical mode of approximately 3 mm of soil moisture per mS/m, and the small standard errors indicate that the EM38 discriminates moisture differences as small as a few mm, and is highly accurate when calibrated. To predict within 10 mm of the true mean of soil moisture content, approximately 5 measurements are required in vertical mode, and approximately 15 in horizontal mode. The absolute accuracy is sufficient for the EM38 to be used in research studies, where it is comparable to, or better than methods based on neutron scattering and time domain reflection.

Raising the EM38 to sample to a range of depths was more effective than we had hoped. Because the EM38 has a non-linear response to depth, it seemed likely that raising EM38 would reduce the quality of the calibrations for shallower measurements. However, good correlation was obtained for both orientations and all heights (Figures 2 and 3). In higher positions, there may have been slightly reduced sensitivity (increased the slope of the relationship, Figures 2 and 3). This was expected, because a smaller volume of soil is sampled as the height of the EM38 increases. Nevertheless, at 0.4 m height in horizontal mode, where the measured soil volume was the least, the relationship between moisture content and ECa has only a small error (standard error = 9 mm). We note that measuring surface soil moisture is often difficult or avoided with a neutron probe (as shields and extra calibrations are required), and soil coring for moisture and bulk density are labour-intensive. The EM38 appears to have considerable advantages over these technologies for repeated measurements of surface soil moisture.

In horizontal mode, the intercept of the calibration curves varied with depth (Figure 3). As sampling depth decreases, less soil and therefore less ECs is measured. The likely intercepts of the ECa data suggest that ECs for each depth is negative for this soil, (Figures 2 and 3). Negative ECs can be explained by dielectric and magnetic conduction in the soil. Current precedes voltage by 90º through a dielectric, which is the opposite (180º difference) of an inductor. Dielectric conduction therefore reduces induction. Magnetic minerals may also negate induction by altering the time-response of currents in soil.

The EM38 was easy and quick to use. Our rate of data collection was typically 400 ECa measurements per hour across a large field. Sampling in a smaller area would be faster.

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