Comparison of soil conductivity measured by ERT and EM38 geophysical methods along irrigated paddock transects on Black Vertosol soils

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Abstract
Electrical resistivity tomography (ERT) and electromagnetic induction (specifically the EM38) are increasingly being used by researchers and agronomists for determining soil properties useful in precision agriculture and environmental monitoring. While the EM38 measures a depth weighted apparent electrical conductivity (EC_a) in the root zone, ERT provides absolute values of bulk electrical conductivity (EC) to great depth. Through field calibrations and empirical relationships these can be converted to estimates of soil water and salinity. There is considerable potential for their concurrent use as they each offer unique advantages in terms of measurement application, however to do this, reasonable conformity between the method outputs is required.

In this study, we compared EC measured by ERT and an EM38 along two transects in irrigated Vertosols. ERT data was inverted and summed using the theoretical cumulative depth response function of the EM38 to obtain comparable ‘derived’ values. EM38 readings were also taken above ground and a field-measured response function calculated. Higher measured responses were found in the surface 0.2 m of soil in vertical dipoles and lower responses in horizontal dipoles, than the theoretical response function, giving a better fit to derived ERT data and potentially improving soil water estimates if used in a soil-water calibration. Trends between derived ERT and EM38 readings were very similar however absolute values were offset. EM38 readings were smaller than ERT values, making comparisons between datasets only possible qualitatively.

Key Words
Resistivity imaging, electromagnetic induction, soil water, soil moisture, clay soil

Introduction

ERT and EM38 are very effective tools for measuring and mapping properties such as soil salinity and soil management zones (Corwin and Lesch 2005). They are also used in a wide number of agronomic and environmental applications to monitor soil water within the root zone or deeper vadose zone. For example- soil water was monitored using ERT throughout an irrigated cropping season by Acworth et al. (2005) to estimate crop uptake and deep drainage; water extraction by trees in agroforestry systems was measured by Huth and Poulton (2007) using an EM38; and historic water movement (under irrigation) into the deeper vadose zone was investigated by Foley et al. (2010) using both EM38 and ERT.

Each geophysical method has unique strengths and application niches in terms of rapidity and detail of time series measurements, soil depth investigated and ease of calibration for estimating soil properties. The EM38 measures a depth-weighted EC_a in the surface (root zone) weighted according to theoretical respective depth response functions (McNeill 1980). Different orientations, coil offsets and depths measured (ground level or above) are used to obtain a range of sensing depths. Soil specific calibrations allow these data to be relatively easily converted to soil water estimates. ERT measures resistivity/conductivity as a function of depth and provides dense datasets of true bulk electrical conductivity (EC) from image inversion (Loke and Barker 1995). Empirical relationships allow these data to be converted to water content, but the process is complex for clay soils and data are often only used qualitatively as a result.

In soil water balance studies, both methods can be used together to greatly enhance the research outcome. For example- the EM38 is ideal for monitoring root zone soil water uptake and deep drainage throughout a cropping season as it can be walked into the field without crop damage and EC_a can be easily calibrated against cored samples to get actual soil water estimates. The movement and fate of the deep drainage in the deeper regolith (beyond the measurement range of the EM38) can be assessed using ERT to image ‘before crop and after crop’ spatial and temporal changes in soil water, as it measures to greater depth and in greater detail than the EM38. However, to dovetail both datasets, conformity between measured EC and EC_a would be required. This possibility is explored within the paper.

Methods

Two transects were imaged on Black Vertosols, 200 km west of Brisbane, used for growing furrow irrigated crops (predominately cotton and sorghum). The first transect, at Brookstead, ran through sparse native vegetation (*Eucalyptus camaldulensis*) and out into a fallow irrigated field. The second transect, at Dalby, ran along a row top in the fallow field. ERT images were taken using an ABEM SAS4000 Terrameter and LUND ES464, with Wenner alpha electrode configuration and an electrode spacing of 0.5 m along 32 m transects, generating detailed 4.5 m deep resistivity profiles (504 measurement points). Field measured apparent resistivity was inverted using RES2DINV version 3.59 (www.geoelectrical.com) to obtain bulk EC. EM38 readings were taken every 2 m on the Brookstead transect, and every 2, 4 or 8 m along the Dalby transect, with the device parallel to the line. Readings were taken on the soil surface in both vertical and horizontal dipoles. Readings were also taken with the EM38 raised above ground surface (called 'depth slicing') in 10 cm increments to 1.5 m in vertical and 0.7 m in horizontal dipoles. A soil coring rig was used to strategically core along transects (cut in 0.3 m depth increments) for soil volumetric water, electrical conductivity (EC), chloride (Cl) and particle size classes.

The EM38 provided single (depth-weighted) values along transects. To compare EC_a measured by the two devices, the depth-weighted response function of the EM38 (McNeill 1980) was applied to the ERT data to generate single 'derived' ERT values along transects. To do this- i) ERT point measures were interpolated as the mid-point between resistivity blocks; ii) data was smoothed using a lateral 0.5 m moving average; iii) for each ERT block depth, the theoretical depth-weighted response function of EM38 vertical and horizontal dipoles were apportioned and applied to ERT data for individual block depths (Table 1) and data summed to depths i.e. to generate a comparative vertical dipole value, 6.8% of the 0-0.2 m ERT reading plus 10% of the 0.2-0.34 m reading etc. were summed down the profile. Field measured response functions were also calculated using EM38 readings taken above ground.

Results and discussion

The two transects provided ideal wet-to-dry comparisons and a range of EC measures. The Brookstead transect was dry under native vegetation (490 mm in top 1.5 m) with soil water content increasing into the irrigated paddock at 16 m (610 mm) (Figure 1a). EC readings were relatively low. In contrast, along the entire Dalby transect the profile was 'wet' and highly conductive (620 mm) except for a dry patch at 12-16 m where a drainage lysimeter is installed (Figure 2a). EC and Cl profiles displayed low surface salt increasing to a salt bulge at 1 m (EC ~1.1 dS/m at both sites, Foley et al. 2010). EC and % clay (65-85%) were very uniform laterally along transects so changes in EC could be mostly attributed to differences in soil water.

Table 1. Theoretical integrated depth contributions to EC_a of the EM38 (McNeill 1980) used to calculate derived ERT values; and site averaged measured response functions– all expressed as fraction of a percent

ERT block depth (m)	Theoretical response function		Brookstead measured response function		Dalby measured response function	
	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
0-0.20	0.068	0.317	0.120 *(0.02)*	0.274 *(0.02)*	0.169 *(0.01)*	0.271 *(0.02)*
0.20-0.34	0.100	0.150	0.108 *(0.01)*	0.143 *(0.02)*	0.120 *(0.01)*	0.160 *(0.01)*
0.34-0.50	0.120	0.117	0.125 *(0.01)*	0.110 *(0.02)*	0.119 *(0.01)*	0.123 *(0.005)*
0.50-0.67	0.113	0.085	0.082 *(0.01)*	0.102 *(0.02)*	0.101 *(0.01)*	0.093 *(0.003)*
0.67-0.86	0.095	0.062	0.091 *(0.01)*	0.017 *(0.02)*	0.087 *(0.01)*	0.014 *(0.006)*
0.86-1.57**	0.198	0.113	0.196 *(0.01)*		0.169 *(0.004)*	
1.57-3.7**	0.172	0.090				
Total[a]	0.87	0.93	0.72	0.65	0.77	0.66

***Italic values are standard deviations of means; ** Several block depths condensed for table brevity**

a – total < 1.0 indicates the response to deeper soil layers.

Measured response functions

Depth slicing has previously been used to create a better interpretation of the EC_a depth distribution with actual weighting functions and response depths found to vary due to EC_a differences among soil layers (Barker 1989). Measured response functions calculated from depth slicing displayed a higher weighting in the top 0.2 m of soil in vertical dipole, and a lower weighting in horizontal dipole, than the theoretical response, for both soils (Table 1). Depth slicing across a range of Vertosols (not presented here) showed a similar trend. When these measured response functions were used to derive ERT values, there was a slightly better fit between the two methods, particularly for high EC_a (Dalby transect). Estimates of profile soil water distribution in near surface layers, from EM38 readings, are likely to be improved if used for these soils.

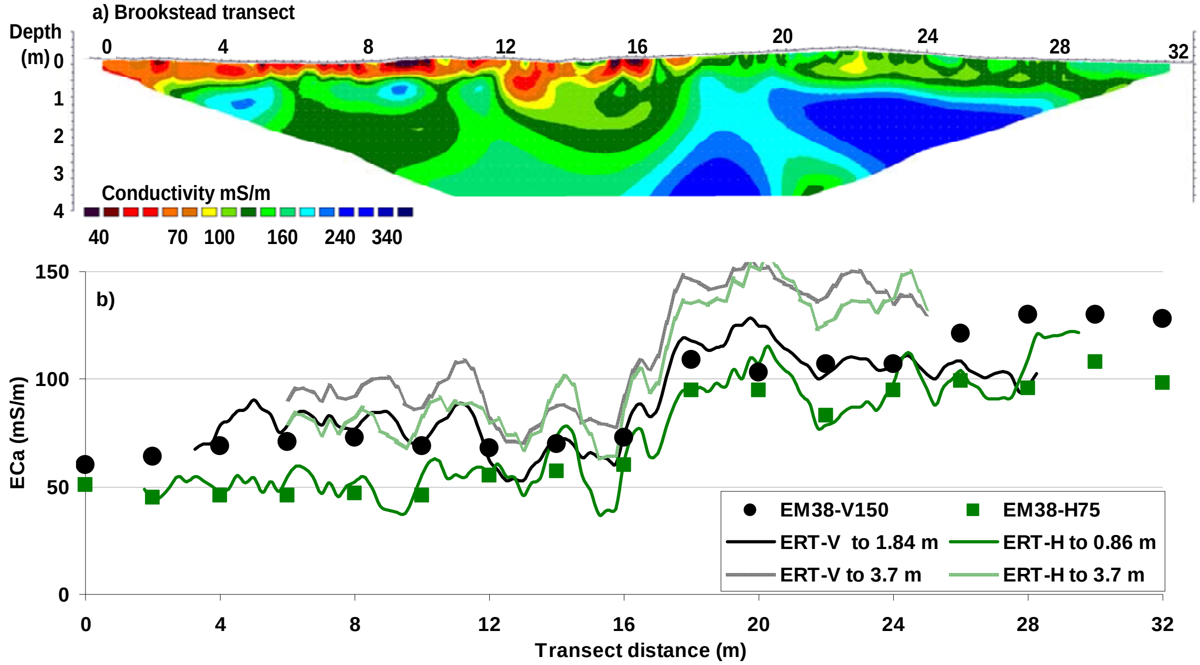

Figure 1. Brookstead transect - a). ERT image profile, b). EC_a measured by the EM38 (points) and comparable integrated depth contributions of EC measured by ERT (moving average lines)

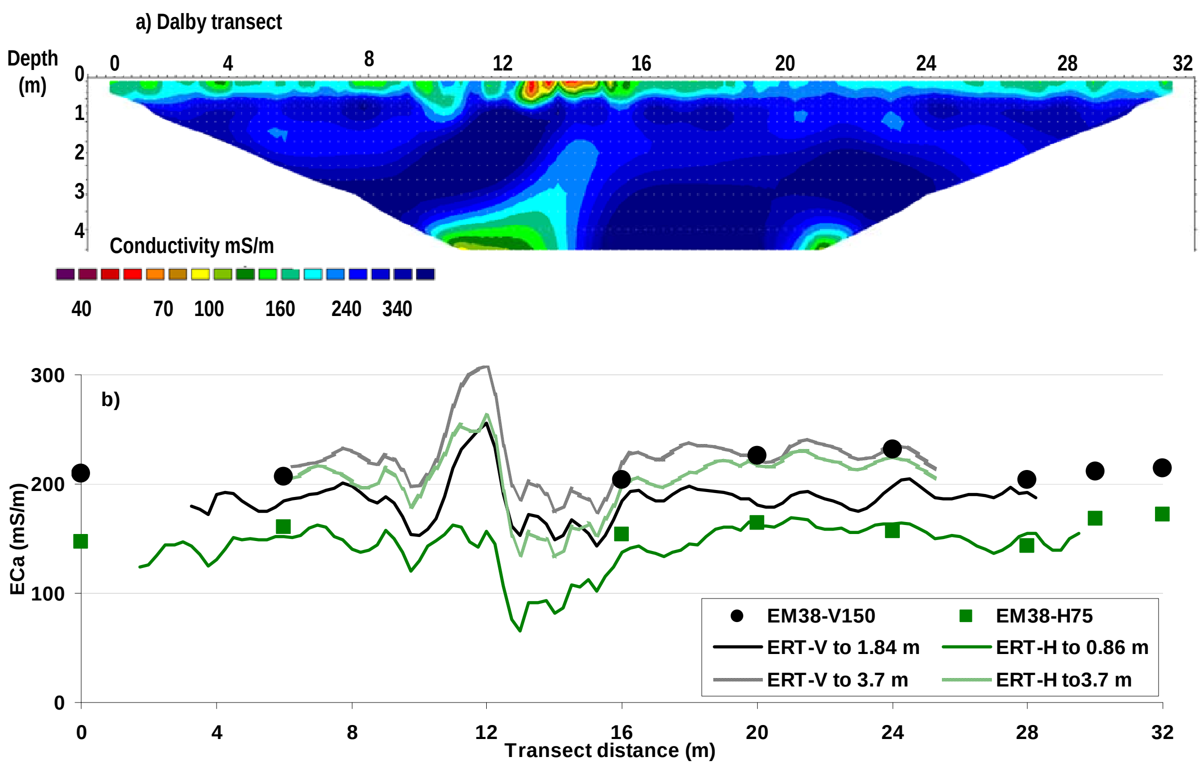

Figure 2. Dalby transect - a). ERT image profile, b). EC_a measured by the EM38 (points) and comparable integrated depth contributions of EC measured by ERT (moving average lines)

ERT and EM38 comparison

Two datasets are presented in Figures 1b and 2b, the solid lines represent derived ERT data summed only to 1.84 m in vertical and 0.86 m in horizontal dipoles and accounting for 73% of the EM38 instrument response. A very good fit between datasets is achieved in both dipoles for all but two EM38 readings (Dalby 20 and 24 m, over the top of an old PAWC wet-up plot). However, the EM38 actually measures to 3-4.5 m in the vertical dipole and 1.75-3 m in the horizontal dipole depending on the EC of the layers (Slavich 1990). Therefore, a second dataset (soft lines) which sums a greater proportion of the theoretic depth response function (to 3.7 m, Table 1) and captures more of the instrument response (87% in vertical and 93% in horizontal dipole) is presented. Of the two datasets it is the truer comparison, although still an underestimate of the total response function. What is very clear for this 'deeper looking' truer function is that while the trends between derived ERT and EM38 readings are very similar and consistent from dry to wet conditions as with the first dataset, absolute values are considerably offset. EM38 readings are smaller than ERT values, making comparisons between datasets only possible qualitatively.

Similar results have been found by other researchers when comparing EMI and ERT (Lavoué et al. 2010; van der Krukl et al. 2011) who found a distinct and considerable shift in absolute values, particularly in the vertical dipole. They attribute these offset differences to the different measurement frequencies used by the methods, different coupling mechanisms (galvanic and inductive) and calibration difficulties with the EM38. These researchers developed linear regressions to correct for differences between EC_a measured by the two methods. They offer two approaches to calculate EC_a from ERT data, the method used here (McNeill theoretical depth response functions) which assumes frequency independence in the range used (potentially erroneous in these clay soils) and a second method using an electromagnetic forward model, which gives a more accurate EC_a especially in highly conductive soils, and includes the frequency dependency and the angle-dependent reflection coefficients between the different soil layers.

Conclusion

Detailed ERT imaging and EM38 measurements were made across a range of soil moisture conditions for two transects on highly conductive swelling clay soils. New depth response functions were derived for the EM38 in vertical and horizontal modes for the Vertosols. Both measured and derived EC_a values were compared and showed very similar trends in data from wet to dry profiles. However, absolute values were considerably offset, with the measured EM38 conductivities considerably lower than co-located derived ERT conductivities. A good match between the EC_a values in these clay soils was not possible, largely due to the different measurement frequencies used in the geophysical techniques. Unless a calibration procedure is used such as linear regression, datasets can only be compared qualitatively. Testing the use of regression calibrations to 'bring the datasets together' to enable quantitative data comparisons to be made would greatly enhance concurrent use of these methods in studies.

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References

Acworth RI, Young RR and Bernadi AL (2005). Monitoring soil moisture status in a Black Vertosol on the Liverpool Plains, NSW, using a combination of neutron scattering and electrical image methods. Australian Journal of Soil Research, 43, 105-117.

Barker RD (1989). Depth of investigation of collinear symmetrical four-electrode arrays. Geophysics, 54, 1031-1037.

Corwin DL and Lesch SM (2005). Apparent soil electrical conductivity measurements in agriculture. Computers and Electronics in Agriculture, 46, 11-43.

Foley JL, Silburn DM and Greve A (2010). Resistivity imaging across native vegetation and irrigated Vertosols of the Condamine catchment—a snapshot of changing regolith water storage. Proceedings of the 19th World Congress of Soil Science, Brisbane, Queensland, 2010, 159-162.

Huth NI and Poulton PL (2007) An electromagnetic induction method for monitoring variation in soil moisture in agroforestry systems. Australian Journal of Soil Research, 45, 63–72.

Lavoué F, van der Kruk J, Rings J, André F, Moghadas D, Huisman JA, Lambot S, Weihermüller L, vanderBorght J, and Vereecken H (2010). Electromagnetic induction calibration using electrical conductivity modeling based on electrical resistivity tomography. Near Surface Geophysics, 8, 3-11.

Loke MH and Barker RD (1995). Least squares deconvolution of apparent resistivity pseudosections. Geophysics, 60, 1682-1690.

McNeill, JD (1980). Electromagnetic terrain conductivity measurements at low induction numbers, Geonics Technical Note, TN-6, Geonics Pty Ltd, Canada.

Slavich P. G. (1990) Determining EC_a-depth profiles from electromagnetic induction measurements. Aust Journal of Soil Research, 28, 443-52.

van der Kruk J, Klotzsche A, Lavoué F, Meles GA, Mester A, Jacob RW, Doetsch JA, Linde N, Maurer H, Green AG and Vereecken H (2011). High resolution hydrogeophysical imaging and characterisation. International Water Technology Journal, I, 35 -45.