Resolving the true electrical conductivity using EM38 and EM31 and a laterally constrained inversion model

John Triantafilis\textsuperscript{A}, Fernando Monteiro Santos\textsuperscript{B}

\textsuperscript{A}School of Biological Earth and Environmental Sciences, University of New South Wales, Sydney, NSW, Australia, Email j.triantafilis@unsw.edu.au
\textsuperscript{B}Universidade de Lisboa, Instituto Don Luis Laboratório Associado, C8, 1749-016 Lisboa, Portugal

Abstract
The ability to map the spatial distribution of average soil property values using geophysical methods at the field level has been well described. This includes the use of electromagnetic (EM) instruments which measure bulk soil electrical conductivity (\(\sigma_a\)). However, soil is a three-dimensional medium. In order to better represent the spatial distribution of soil properties with depth, methods of inverting \(\sigma_a\) data have been attempted (e.g. Tikhonov regularisation). In this paper we employ a 1-D inversion algorithm with 2-D smoothness constraints to predict true electrical conductivity (\(\sigma\)) using \(\sigma_a\) data collected along a transect in an irrigated field in the lower Namoi valley. The \(\sigma_a\) data includes the root-zone measuring EM38 and the vadose-zone sensing EM31: in the vertical (v) and horizontal (h) dipole modes and at heights of 0.2 and 1.0 m, respectively. In addition, we collected EM38 \(\sigma_a\) at heights of 0.4 and 0.6 m. In order to compare and contrast the value of the various \(\sigma_a\) data we carry out individual inversions of EM38v and EM38h collected at heights of 0.2, 0.4 and 0.6 m, and EM31v and EM31h at 1.0 m. In addition, we conduct joint inversions of various combinations. We find that the values of \(\sigma\) achieved along the transect represent the duplex nature of the soil. In general, the EM38 assists in resolving solum and root zone variability of the cation exchange capacity (CEC – cmol(+) / kg of soil solids) and the electrical conductivity of a saturated soil paste extract (EC\(_e\) – dS/m), whilst the use of the EM31 assists in characterising the vadose-zone and the likely location of a shallow perched-water table. In terms of identifying an optimal set of EM \(\sigma_a\) data for inversion we found that a joint inversion of the EM38 at a height of 0.6 m and EM31 signal data provided the best correlation with electrical conductivity of a saturated soil paste (EC\(_p\) – dS/m) and CEC (respectively, 0.81 and 0.77).

Key Words
Drainage channels, digital soil mapping, EM38, EM31, electromagnetic (EM) induction, EM inversion

Introduction
The application of electromagnetic (EM) induction instruments for digital soil mapping has increased over the last 10 years. For example, the EM38 has been used to map management zones (Triantafilis et al. 2009a) and map the spatial distribution of average soil moisture (Tromp van Meerveld and McDonnell 2009), soil salinity (Wu et al. 2009), deep drainage (Triantafilis et al. 2003), depth to water table (Buchanan and Triantafilis 2009), clay content (Triantafilis et al. 2001) and CEC (Triantafilis et al. 2009b). However, management of soil requires information about the vertical distribution of its properties. In order to determine this, various approaches have been proposed. The best examples appear in relation to describing soil salinity. Australian examples include logistic profile modeling (Triantafilis et al. 2000). A less site-specific approach involves the reconstruction of the true electrical conductivity (\(\sigma\)) profile itself. Cook and Walker (1992) developed a method using linear combinations of \(\sigma_a\) measurements to estimate \(\sigma\) at a depth interval of interest. Borchers et al. (1997) and Hendrickx et al. (2002) used Tikhonov regularization for estimating \(\sigma\) within a soil profile. The aim of this study is to use EM imaging and \(\sigma_a\) collected by an EM38 and EM31 to infer the spatial distribution of soil properties related to \(\sigma_a\) across an irrigated cotton field in the lower Namoi valley. We compare these models qualitatively and quantitatively with estimated and measured soil laboratory data including: volumetric moisture content (\(\theta\)); electrical conductivity of a saturated soil paste extract (EC\(_e\) – dS/m) and extract (EC\(_s\) - dS/m); clay content (%); and, cation exchange capacity (CEC - mmol(+) / kg of soil solids).

Methods
The study field is located 3 km southeast of Wee Waa (Figure 1) which is situated in the lower Namoi valley of northern New South Wales (30.24°S, 149.48°E). It is located at the northern edge of the Pilliga Scrub. A large drainage channel is evident at the northern end of the field. EM data collection involved acquisition along a transect using a Mobile Electromagnetic Sensing System-
MESS (Triantafilis et al. 2002). Here EM38 measurements are made in the vertical (EM38v) and horizontal (EM38h) modes. Given the operating frequency (i.e. 14.5 kHz) and coil spacing (1.0 m), the depth of exploration is 1.5 and 0.75 m (McNeill 1990), respectively, when the instrument is placed on the ground. In this study we measure EM38v and EM38h $\sigma_a$ at heights of 0.2, 0.4 and 0.6 m. The larger coil spacing (3.7 m) and smaller operating frequency (9.8 kHz) of the EM31 enable exploration depths of 6 and 3 m, when measured in the vertical (EM31v) and horizontal (EM31h) mode and 1.0 m (McNeill 1980), respectively. The EM38 and EM31 $\sigma_a$ is passed through a modified version of a 1-D laterally constrained method (i.e. EM34-2D) developed by Monteiro Santos (2004). We use a damping factor ($\lambda$) of 0.6 with inversions modelled onto a 2 m mesh spacing along the transect at depths of: 0.075, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 0.95, 1.05, 1.17, 1.28, 1.40, 1.53, 1.67, 1.80, 1.95 and 2.1 m.

To validate the EM inversions, 9 sites are available along the transect: Site 22 in the south to site 14 in the north. These were chosen to account for the range of EM $\sigma_a$ data values (Triantafilis et al. 2009b). At each site soil was sampled at 0.30 m depth increments to 2.1 m. The samples were analysed for: gravimetric soil moisture content ($\omega$ - %), electrical conductivity of a saturated soil paste ($EC_p$ - dS/m) and its extract ($EC_e$ - dS/m) and the saturation percentage (SP). We calculate $\theta$ (cm$^3$/cm$^3$) from $\omega x \rho$, where we estimate bulk density ($\rho$ - g/cm$^3$) using $\rho = 1.73 - 0.0067 x SP$ (Rhoades et al. 1989). Particle size fraction is determined using the hydrometer method with the soil texture class and grade determined. We estimate cation exchange capacity (CEC - mmol(+)/kg) using a mechanical leaching device (Tucker 1974; Holmgren et al. 1977).

Results and Discussion

Figure 1 shows the spatial distribution of EM38 and EM31 $\sigma_a$ measured in various modes of operation and at several heights along transect 3. The following points summarize the $\sigma_a$ data: i) $\sigma_a$ patterns are similar; ii) $\sigma_a$ is larger in the vertical than the horizontal mode for both instruments; iii) EM31 $\sigma_a$ is larger than equivalent EM38 $\sigma_a$; iv) EM38 data decreases with increasing height: v) $\sigma_a$ generally decreases from south to north (i.e. tail ditch); vi) Difference in $\sigma_a$ in vertical and horizontal mode is larger in the south.

Figure 2a shows the plot of estimated volumetric soil water content ($\theta$) with depth. Topsoil and subsurface clay is small (< 20 %) and equates to a loam to silty loam texture class (Texture Group - 3). At the southern end subsoil clay content (i.e. 22, 21, 20 and 19) is intermediate (i.e. 25-40 %) varying from a clay loam (Texture Group - 4) to light clay (Texture Group - 5). In the centre and north (i.e. 18, 17, 16, 15 and 14) subsoil clay (> 40 %) falls within the light-medium to heavy clay class (Texture Group - 6).
Figure 2d shows the topsoil is characterized by uniformly small CEC (i.e. < 9 cmol(+) /kg of soil) with CEC intermediate to large in the subsoil. At the southern end subsoil CEC is largest (i.e. > 18 cmol(+) /kg of soil), whilst in the north CEC ranges from small (9 cmol(+) /kg of soil) to intermediate (12-15 cmol(+) /kg of soil). With regard to EC_e, Figure 2e shows a small amount of salt has accumulated in two of the cores at the southern end. Interestingly site 19 exhibits salt levels equivalent to the profiles at the northern end (i.e. < 1.5 dS/m). Figure 1e shows measured EC_p. It represents the overall σ of the samples collected and is therefore a measure of the various soil properties known to influence σ_a. Figure 3a, b and c shows the spatial distribution of σ considering the inversion of the EM38 σ_a data at a height of 0.20, 0.4 and 0.6 m, respectively. The 2-D distribution of σ reflects the spatial distribution of θ and the duplex nature of the soil.

The pattern of σ corresponds better with spatial distribution of CEC, EC_e and EC_p. The sandy to loamy sand topsoil (0-0.3 m) and subsurface (0.3-0.6 m) horizons are characterized by smaller σ (< 30 mS/m). At the northern end, intermediate-large σ (60-120 mS/m) characterize the medium clay textured subsoil horizon. Interestingly, the largest σ values (>120 mS/m) characterize equivalent medium clay and clay loam textured subsoil horizons in the centre and southern end, respectively. This is because the subsoil is more reactive, as evidenced by larger values of CEC (Figure 2d).

It is also worth mentioning that given the soil profiles along most of the transect are duplex in nature, we might have expected to resolve a sharp change in σ at a depth of around 0.30 m. The change in σ is gradual, however, with topsoil and subsurface σ (30 mS/m) changing to larger values in the subsoil (> 120 mS/m) over a depth range of 0.6 m. Nevertheless, the inversion of the EM38 σ_a data has been able to detect the extent of a known minor drainage channel at 6651750 and represented by the slot of small to intermediate values of profile σ (90-120 mS/m). This location is aligned with soil sampling site 19. In addition, a second minor drainage channel may also have been identified at 6651650.

To represent the spatial distribution of σ within the solum, we conducted various joint inversions. Figure 3d shows the σ profile achieved using the EM38 σ_a at heights of 0.4 and 0.6 m. The change in σ occurs over a smaller depth. An explanation is that as the EM38 is raised a larger proportion of the measurement is contributed by the less reactive topsoil and subsurface. However, the deep subsoil representation of soil is diminished, as is our ability to differentiate the clay mineralogy at either end of the field.

The deeper subsoil is better represented when we invert the EM31 data (Figure 3e). The large values of σ that characterise the deeper subsoil at the southern end of the field may be attributable to the presence of a shallow perched water table. Our ability to resolve topsoil and subsurface features are poor, however.
The spatial distribution of $\sigma$ developed from joint inversions between the EM31 and EM38 at individual heights of 0.2, 0.4 and 0.6 m are shown in Figure 4a, 4b and 4c, respectively. Joint inversions are also shown for various other combinations. In terms of determining an optimal set of $\sigma_a$ data, we found that the use of the EM38 $\sigma_a$ at a height of 0.6 m and EM31 data (Figure 4c) led to the highest correlation with $EC_p$ (0.81).

**Conclusion**

The spatial distribution of topsoil, subsurface and subsoil properties are discernible by the inversion of $\sigma_a$ data collected along an intensively surveyed transect within an irrigated cotton growing field south-east of Wee Waa. The root-zone model, where the EM38 $\sigma_a$ data (EM38v and EM38h) available at heights of 0.20, 0.4 and 0.6 m discard the major soil types and physiographic features within the field. This includes: the duplex soil profiles with more reactive clay (> 12 cmol(+)kg) at the southern end of the field and the duplex soil profiles associated with a prior stream at the northern end. The location of two minor drainage channels, equivalent to the soil that characterises the northern end are discerned at the southern end.

To better resolve the duplex nature of the soil we develop a solum model, which involved passing the entire EM38 $\sigma_a$ data set (EM38v and EM38h) available at various heights (0.20, 0.40 and 0.60 m) through our 1-D inversion algorithm. Whilst we are able to better represent the clear and abrupt change in clay content, the inversion model is unable to resolve differences in subsoil $\sigma$ of the two types of soil profile that characterize the northern and southern end of the field. The use of the EM31 $\sigma_a$ data in reconstructing $\sigma$ in the root-zone appears to be limited. Its greatest contribution is in characterizing and defining the lower boundary. This conclusion is borne out when we developed two joint EM inversion models of the soil and vadose-zone (e.g. developed by entering the EM38v and EM38h $\sigma_a$ data available at various heights. Statistical analysis showed that the best correlation with $EC_p$ (0.81) is achievable by jointly inverting the EM38 $\sigma_a$ at a height of 0.60 m with the EM31 $\sigma_a$ data. The approach we have used has been applied to the joint inversion of EM38 and EM34 $\sigma_a$ data (Triantafilis and Santos 2009) as well as to a DUALEM-421 (Monteiro Santos et al. 2009).