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www.publish.csiro.au/journals/ajsr *Australian Journal of Soil Research*, 2007, **45**, 63–72

An electromagnetic induction method for monitoring variation in soil moisture in agroforestry systems

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Abstract. An understanding of the spatial and temporal patterns of soil water extraction by trees in agroforestry systems has long been seen as an important step towards understanding their functioning. Traditional methods of soil moisture monitoring have been employed with some success but limitations in utilising them efficiently across both time and space have led to restrictions in their use. An electromagnetic induction (EMI) technique has been evaluated and used to study the patterns of soil water extraction from a Grey Vertosol in fallow or cropped fields alongside a *Eucalyptus argophloia* windbreak near Warra, Qld (26.93°S, 150.93°E). This technique provides methods for minimising error caused by seasonal variations in temperature and the vertical distributions of both soil water and temperature. The calibration developed in this study was successful in describing the observed variations in total soil moisture in the surface 0.9 m of the soil profile ($R^2 = 0.93$, s.e. = 15.3 mm). We conclude that EMI techniques can provide a quick and efficient means for monitoring soil moisture patterns in agroforestry systems when employed under suitable conditions. This paper describes the techniques developed and where they may be employed, the type of information available from the approach, and the likely methods for employing EMI approaches in a wider range of situations.

Additional keywords: EM38, soil electrical conductivity, soil temperature, *Eucalyptus argophloia*.

Introduction

The conversion of much of Australia's low to medium rainfall zone to agricultural production has been achieved via the removal of large areas of the native vegetation, which has led to major shifts in the functioning of these landscapes. For example, changes in the hydrological balance of many areas now mean that the threat of salinisation is among the greatest challenges to the dryland farming systems of Australia (NLWRA 2000). At the same time, the loss of trees has impacted upon local biodiversity which had relied on the previous woodland for food and shelter. As a consequence there is considerable interest in Australia for capturing the expected long-term benefits of retaining or planting trees on farms to rehabilitate the land (Prinsley 1992; Stirzaker *et al*. 2002; Vesk and Mac Nally 2006).

However, in systems where water is a major limitation, the competition for this important resource can have a detrimental impact on commercial crop production. Studies in Australia (e.g. Knight *et al*. 2002; Sudmeyer *et al*. 2002; Woodall and Ward 2002; Unkovich *et al*. 2003) and overseas (e.g. Akbar *et al*. 1990; Kohli *et al*. 1990; Malik and Sharma 1990; Onyewotu and Stigter 1995) have shown that where water availability is a major determinant of crop production, trees are able to compete very effectively for this resource. Attempts have been made to manage tree root systems via root pruning (Sudmeyer *et al*. 2002; Woodall and Ward 2002) or barrier systems (Singh *et al*. 1989) with varied success. The economic viability of such an intervention is also by no means assured. Therefore, we have been interested in determining if a better understanding of the functioning of tree root systems, and the spatial and temporal patterns of tree-crop competition, could highlight simple alterations in crop management to restore the balance in favour of commercial crops where there is tree-crop competition. To achieve this, a methodology for quickly and efficiently monitoring patterns of soil water content is needed.

Monitoring of soil water extraction within the tree-crop competition zone is not novel. Many techniques have been employed. These include, for example, simple gravimetric sampling of soil water (Malik and Sharma 1990; Kidanu *et al*. 2005), gypsum blocks (Lehmann *et al*. 1998), time domain reflectometry (Hou *et al*. 2003), and neutron scattering techniques (Story 1967; Singh *et al*. 1989; Eastham and Rose 1990; Knight *et al*. 2002; Sudmeyer *et al*. 2002; Woodall and Ward 2002; Ellis *et al*. 2005). While traditional methods of soil moisture monitoring have been employed with some success, limitations in employing them efficiently across both time and space have led to restrictions in their use. These approaches can be labour-intensive and so logistical constraints on the number and placement of monitoring sites is always a concern for researchers. At the same time, apparatus employed within a growing season need to be utilised without affecting the crop. Electromagnetic induction (EMI) has known advantages over

10.1071/SR06093 0004-9573/07/010063

other methods, including non-use of radioactivity, speed and ease of use, and its non-invasive nature (Reedy and Scanlon 2003). For these reasons, an EMI technique was developed to enable us to repeatedly monitor a large number of sites over an extended period in both fallow and cropped fields.

EMI techniques are regularly used to assess soil spatial variability, especially in precision agriculture (Corwin and Plant 2005). They have been used to study variations in soil depth (Bork *et al.* 1998), soil type (Greve and Greve 2004; Triantafilis and Lesch 2005), salinity (Bennett and George 1995; Triantafilis *et al.* 2000), and the risk of deep drainage of water (Triantafilis *et al.* 2004). EMI provides a measure of the apparent bulk electrical conductivity (EC_a) of the soil profile, and as this is affected by variation in soil moisture, the technique has also been employed to study the variability of soil moisture across fields (Kachanoski *et al.* 1988; Reedy and Scanlon 2003). An extensive list of the range of applications for EMI techniques in agricultural systems is included in Corwin and Lesch (2005*a*). The following describes how such EMI techniques can be employed in studying agroforestry systems.

Background

EMI techniques basically consist of a measure of the bulk soil EC_a. The EM38 (Geonics Ltd, Canada) measures the bulk soil EC_a by inducing a small current within the soil via a primary electromagnetic field from a transmitting coil and measuring the resultant secondary field via a receiving coil. If we assume the response functions given by McNeill (1980) hold for heterogeneous profiles, the EM measurements for the vertical and horizontal dipole can be represented as:

$$EC_v = \int_0^\infty EC_a(z)\,\phi_v(z)\partial z \tag{1a}$$

$$EC_h = \int_0^\infty EC_a(z)\,\phi_h(z)\partial z \tag{1b}$$

where z is depth expressed as ratio of depth to the intercoil spacing, $EC_a(z)$ is the value of EC_a (dS/m) at depth z, and $\phi_v(z)$ and $\phi_h(z)$ are density functions representing the relative contribution with depth for the vertical and horizontal dipoles, respectively. The intercoil spacing for the EM38 is 1 m, and so for simplification, z shall be referred to as depth within a soil profile for the rest of this paper. Under low-induction number conditions (i.e. nonsaline areas) the density functions will be independent of earth conductivity and are given via the following (McNeill 1980) and are shown in Fig. 1:

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

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

Cook and Walker (1992) showed that linear combinations of EC_v and EC_h can be further used to create a density function that better matches the portion of the soil profile under study. For example, we have employed a combination of 1 reading of the EM38 in both the vertical and horizontal dipole configurations as follows:

$$EC_t = \alpha_v\,EC_v + \alpha_h\,EC_h \tag{3}$$

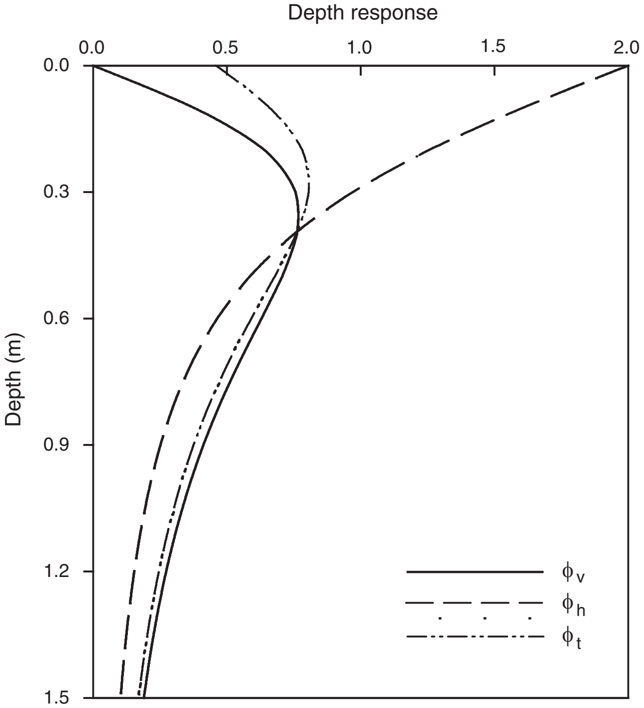

Fig. 1. Depth response functions for EM38 used in either the vertical, $\phi_v(z)$, or horizontal dipole, $\phi_h(z)$. The linear combination of these, $\phi_t(z)$ (Eqn 3, $\alpha_v = 0.77$, $\alpha_h = 0.23$) is shown for comparison.

where EC_t (dS/m) is the weighted average of the measurements. To ensure that the combination of measurements represents the EC_a of a hypothetical uniform profile, the following constraints must hold:

$$\int_0^\infty \phi_v(z)\partial z = \int_0^\infty \phi_h(z)\partial z = \int_0^\infty \phi_t(z)\partial z = \alpha_v + \alpha_h = 1 \tag{4}$$

The first 2 constraints are maintained if the EM38 readings are taken with the unit placed on the soil surface, and the third constraint is maintained by the combination of the other constraints. If these are all maintained, values of α_v and α_h can be derived to create density functions emphasising any portion of the soil profile. Cook and Walker (1992) do remind us, however, that the error in the individual measurements EC_v and EC_h will be magnified by the values of α_v and α_h and so values should be chosen to minimise any increase in measurement error.

In this study, an alternative approach to Cook and Walker (1992) for selecting weighting factors has been employed. Rather than determining values to maximise the proportion of the density functions within a given soil region, we have selected values that provide a relatively constant density function within the area of interest, that is, the region from the soil surface to 0.9 m depth. Values were determined via an optimisation procedure that minimised the average variation of $\phi_t(z)$ $(= \alpha_v.\phi_v(z) + \alpha_h.\phi_h(z))$ about the mean value in this region, thus removing bias in the signal from either deep or near surface conditions. Furthermore, the value of both weighting factors was constrained to <1.0 so as to not amplify any measurement error. Values of α_v and α_h of approximately 0.77 and 0.23, respectively, were found to provide a sufficiently even density function and have been used when required (Fig. 1).

When using the EMI approach over an extended period of time in the field, the seasonal variation in soil temperature is likely to affect the values of EC_v and EC_h recorded by the EM38 due to the temperature dependency of the bulk soil electrical conductivity. Slavich and Petterson (1990) calculated temperature correction factors for various times of year for Griffith, NSW, via a regression analysis on an array of various synthetic EC_a profiles. They found that while the correction factors varied widely with season, they were not significantly effected by of the shape of the EC_a profile. If that is the case, and if we assume that temperature corrections for soil solution conductivity apply also to EC_a, we can calculate the likely EC_v and EC_h temperature corrections factors from an estimate of the soil temperature profile as follows:

$$\tau_v(t) = \int_0^\infty \tau(T(z,t))\,\phi_v(z)\partial z \tag{5a}$$

$$\tau_h(t) = \int_0^\infty \tau(T(z,t))\,\phi_h(z)\partial z \tag{5b}$$

where τ is the temperature correction factor to convert the conductivity of a soil solution back to that of an equivalent solution at 25°C, and T is soil temperature (°C).

τ can be determined (Richards 1954) according to:

$$\tau(T) = \frac{1}{1 + 0.0191 \times (T - 25)} \tag{6}$$

Even though this approach is slightly more complex than that employed by Reedy and Scanlon (2003), who simply calculated the correction based upon the average temperature within the instrument's measurement zone, it is expected that it will better account for the seasonal differences in temperature profiles and the instrument's density function.

In order to integrate τ across the EMI density function, we require information regarding the variation of soil temperature with depth. Because it is impractical to expect knowledge of soil temperature at depth for each point and each sample date measured with the EM38, a simple model of the variation of soil temperature throughout the annual temperature cycle was used. The simple model need only describe the increasingly damped and lagging oscillations of temperature with increasing soil depth in order to capture the major effects of seasonal changes in soil temperature on EMI measurements. Such a model (West 1952) can be expressed as:

$$T(z,t) = \overline{T} + \frac{A}{2} \times e^{\frac{-z}{z_d}} \times \cos\left(\frac{(t - t_0)2\pi}{365.25} - \frac{z}{z_d}\right) \tag{7}$$

where $T(z,t)$ is the soil temperature (°C) at a given position and time, z_d is the soil temperature damping depth (m), t is time specified as day of year, t_0 is the hottest day of the year, and finally $\overline{T}$ and A are the annual average and amplitude in soil near-surface temperature (°C).

Therefore, in order to approximate a value of τ to correct an EMI reading to a value that would correspond to a standard profile with a uniform temperature of 25°C, one would need to provide a value of $\overline{T}$, A, z_d, and the time of measurement. The first three can be easily calculated from long-term soil temperature data, such as those provided by the Australian Bureau of Meteorology (www.bom.gov.au).

Surface soil temperatures were assumed to reach a maximum on 11 January (i.e. $t_0 = 11$) (West 1952). It is also assumed that the damping depth for diurnal soil temperature oscillations is sufficiently low that the long-term daily temperature at 1 m depth can be used to provide the value of $\overline{T}$. The remaining parameters were then calculated from the observed annual variation in soil temperature at 0.5 and 1.0 m depths from Eqn 7 as follows:

$$z_d = \frac{1 - 0.5}{\ln(A_{0.5}/A_{1.0})} \tag{8}$$

$$A = A_{1.0} \times e^{\frac{1}{z_d}} \tag{9}$$

where $A_{0.5}$ and $A_{1.0}$ are the amplitudes of the annual soil temperature oscillations (°C) at 0.5 and 1.0 m depths respectively. These were calculated from the difference between the 5th and 95th percentiles for the long-term data. Finally, the amplitude at the surface was deduced once again from Eqn 7 by substituting the calculated effective damping depth and the amplitude at 1 m.

All that remains now is to relate EC_a to the average water content for the profile. For a given unit of soil, the relationship between EC_a and soil volumetric water content (θ) can be approximated as follows (Rhoades *et al.* 1976; Cook and Williams 1998):

$$EC_a = EC_s + EC_w \times \theta \times \eta \tag{10}$$

where EC_s (dS/m) is the solid phase contribution to EC_a, EC_w (dS/m) is the electrical conductivity of the soil solution, and η is the tortuosity ($0 < \eta < 1$); η will be determined by factors such as soil texture and moisture content, and so one could imagine θ affecting EC_a in a complex manner. However, investigation of results from the field study described below suggested that, overall, a linear relationship between θ and EC_a existed. Similar results have been found in other studies (e.g. Reedy and Scanlon 2003). That being so, the following relationship has been used to explain the variation in EC_a between wet and dry conditions:

$$EC_a = EC_{ll} + \kappa \times \theta \quad (\text{where } \theta > \theta_{ll}) \tag{11}$$

where EC_{ll} (dS/m) is the value of EC_a at θ_{ll} (m^3/m^3), the lower limit of plant water extraction. The similarity between Eqns 10 and 11 indicates that the basic underlying principles are maintained. EC_{ll} captures the conductivity of the solid phase and remainder of the right-hand side captures the effect of the liquid phase conductivity and soil water pore space effects.

To summarise, to calculate the average soil moisture for a chosen depth of the soil, one would calculate a value of EC_t from values of EC_v and EC_h, both modified using τ_v and τ_h for the current calendar day, and use a linear calibration equation to convert this value to soil moisture content. Data from the experiment described below have been used to determine if such a linear calibration can be used to effectively monitor changes in soil moisture. The methods for determining τ from basic annual soil temperature patterns will also be evaluated.

Method

Monitoring of tree-crop competition has been undertaken at a farm near the township of Warra, Qld (26.93°S, 150.93°E) where a belt of 4 rows of *Eucalyptus argophloia* at approximately 5 by 5 m spacing has been planted along the edge of fields used for the production of wheat, cotton, and chickpeas. At the commencement of the study the trees were approximately 7 years old with a height of 10 m. This site has been previously studied for the impacts of these trees on commercial cropping (Huth *et al.* 2002). The soils of the area have been characterised as self-mulching Grey Vertosols (Isbell 1996; Dalgliesh and Foale 1998; Harris *et al.* 1999) and analyses of soil attributes likely to impact EMI measurements were undertaken (Table 1). Two neighbouring cropping bays were selected to enable the study of soil water extraction by the trees in both cropped and fallow land during the same season. Investigation of aerial photographs from the past 60 years indicated that the area adjacent to the trees has been managed uniformly for a considerable time and there was no visual indication of variation in surface soil within the portion of the field to be monitored.

Soil sampling to depth had been occurring within these fields as part of other studies into the movement of salts under agricultural management. EM38 readings in both the vertical and horizontal dipole were taken before each soil sampling in order to construct a calibration dataset consisting of paired values of both soil moisture and EC_t. In order to extend the range of moisture and temperature conditions encompassed by the calibration set, opportunistic samples were added at various times of the year at different distances from the trees. Each soil sample consisted of a pair of soil cores in order to account for soil variability (Corwin and Lesch 2005*b*).

The monitoring of soil moisture and its extraction by both trees and crops was undertaken using transects of EC_v and EC_h taken at 5-m intervals from 0 to 50 m from the belt of trees in both fallow fields and those sown to wheat crops during the winters of 2004 and 2005. These transects were replicated 4 times in each of 3 neighbouring fields. In the summer of 2004–2005, one of the fields was sown to cotton using a ‘double-skip’ configuration (Bange *et al.* 2005) in which every third and fourth row is not planted in order to maximise available soil water during dry growing seasons. A similar planting strategy has been described for sorghum by Whish *et al.* (2005). In this case, it was necessary to increase the sample density in order to correctly sample the variation in soil moisture induced by the sowing geometry. The flexibility of the EMI approach was tested by increasing the sampling density to match the sowing geometry. EC_a measurements during this cropping season were taken between the twin cropped rows and at the mid-point of the ‘skipped’ rows, resulting in readings recorded every 2 m along each transect within the cotton crop. On each measurement occasion, measurements were taken over a short time period, and the instrument was kept shaded when not in use in order to minimise the risk of instrument drift due to variations in temperature within the apparatus (Robinson *et al.* 2004). Although previous work has shown little effect of diurnal temperature variation on EC_a (Brevik *et al.* 2004), measurements were also always taken mid-morning to coincide with when the surface soils might be at the daily average temperature.

A calibration, of the form of Eqn 11, for total soil moisture in the surface 0.9 m was derived from the paired soil moisture and EMI measurements. EC_v and EC_h measurements were corrected utilising Eqn 5. The parameters for the annual soil temperature time course described by Eqn 7 were derived from 12 years of soil temperature data for the nearby township of Dalby (27.17°S, 151.27°E).

Results

Tests for the relative influence of various soil properties upon the variation in EMI measurements indicated that soil moisture was by far the major factor for our experimental area. For sampling occasions in which chemical, moisture, and EMI measurements were all available, simple correlation analysis with surface (0–0.9 m) soil attributes found that soil moisture could describe most of the variation ($R^2 = 0.9$, $P = 0.0011$) in corrected EMI measurements, whereas soil chloride ($R^2 = 0.003$, $P = 0.91$) or $EC_{1:5}$ ($R^2 = 0.03$, $P = 0.72$) were poorly correlated. This is not surprising given the low level of variation in surface soil chemical and physical attributes (Table 1) and the high level of variation in soil moisture.

In order to utilise the above equations, one would first have to verify that Eqn 5 could be used to calculate an effective temperature correction factor. We first compared the results of Eqn 5 to the correction factors of Slavich and Petterson (1990) constructed from the data of West (1952) for Griffith, NSW. The

Table 1. Some published soil attributes for a Grey Vertosol at Warra, Qld, and means (standard deviations in parentheses) of various soil properties for the experimental site

Data represent the combination of 6–8 sampling locations with replicated cores at each site as suggested by Corwin and Lesch (2005*b*)

Depth (m)	BD^A (Mg/m^3)	$\theta_{LL}{}^{A,B}$ (mm^3/mm^3)	$\theta_{DUL}{}^A$	OC (%)	$EC_{1:5}$ (dS/m)	Cl (µg/g)	Clay (%)
0.00–0.15	1.39	0.22	0.40	0.62 (0.06)	0.21 (0.02)	17.4 (3.6)	51.1 (3.0)
0.15–0.30	1.35	0.21	0.41	0.47 (0.06)	0.25 (0.04)	35.7 (14.7)	55.0 (4.6)
0.30–0.60	1.35	0.22	0.41	0.41 (0.05)	0.37 (0.10)	150.7 (83.3)	–
0.60–0.90	1.43	0.24	0.38	0.29 (0.03)	0.59 (0.15)	423.9 (124.7)	–
0.90–1.20	1.44	0.26	0.38	0.23 (0.05)	0.76 (0.13)	728.6 (180.4)	–
1.20–1.50	1.45	0.34	0.37	0.21 (0.04)	0.82 (0.15)	873.7 (182.2)	–

[A] Bulk density, lower limit of plant available soil water and drained upper limit from Dalgliesh and Foale (1998).

[B] Lower limit for cotton crop.

comparison (Fig. 2*a*) shows clearly that a simple application of Eqn 5 can reproduce the results of their regression analysis. In reality, this is not surprising given their finding that the shape of the soil EC_a profile has little effect on the resultant temperature correction factor. The same process was then followed to compare Eqn 5 to the correction factors employed by Bennett and George (1995) for Perth and Albany in Western Australia. In this study, as is often the case in the scientific literature, the authors assumed the whole profile correction factor from the average value of τ calculated from soil temperatures at 0.5 and 1 m. Figure 2*b* shows that the divergence from that obtained from Eqn 5 can be significant. The possible error in the Bennett and George (1995) approach introduced by the lagged temperature response is clearly evident. Surface soil temperatures will be responding to spring warming earlier than at the depths used by Bennett and George (1995), and so a lag in the temperature corrections is especially evident in τ_h. At the same time, the temperature data for Perth suggest that the damping depth is much greater at this location and surface temperatures fluctuate more widely on a seasonal basis. The simple model encapsulated in Eqn 7 captured this adequately and thus led to a much a wider range in correction factors. It must be noted that all this extra information was constructed from the same amount of data (i.e. soil temperatures from 0.5 and 1 m) simply through the use of Eqns 8 and 9. These findings would suggest that the approach described in this paper was as effective as the more complex approach of Slavich and Petterson (1990), and possibly more effective than the simpler approach of Bennett and George (1995), but with no further input requirements.

A variety of soil moisture conditions were used in the development of the calibration equation as can be seen in Fig. 3. Profiles located close to the trees were often at, or very close, to the lower limit of plant-available soil water for the eucalypts. Samples taken further from the trees, or in the open field, usually contained higher water contents, extending to some close to this soil's drained upper limit (Dalgliesh and Foale 1998), thus ensuring that we had sampled across most of the range of plant available water content. Variation in the distribution of soil water with depth also ensured that we had collected a dataset encompassing most of the soil moisture conditions likely to be observed during our experimental observations.

The weighting factors, α_v and α_h, used in the calculation of EC_t, were chosen to minimise spatial bias in the surface 0.9 m of the soil profile. We therefore calculated the total soil moisture in the surface 0.9 m of the soil profile (SW_{90}) and regressed this against the value of EC_t calculated from EMI measurements taken at the time of soil sampling. A high correlation between EC_t and SW_{90} was found as illustrated in Fig. 4. This figure also includes a comparison with data not used in formulating the calibration equation. These data were measured in neighbouring fields or within the same field but at points known to have a variation in soil properties. Some of these excluded sites exhibit a visible variation in surface soil colour and others differ in their management history. These suggest that differences in clay and salt content of the soil may be the cause of the variation from the trend indicated in the calibration data. This highlights the need for consideration of soil variability when choosing the location of both study and calibration sites.

The results of the calibration exercise suggest that, in our initial choice of location, we have been successful in identifying

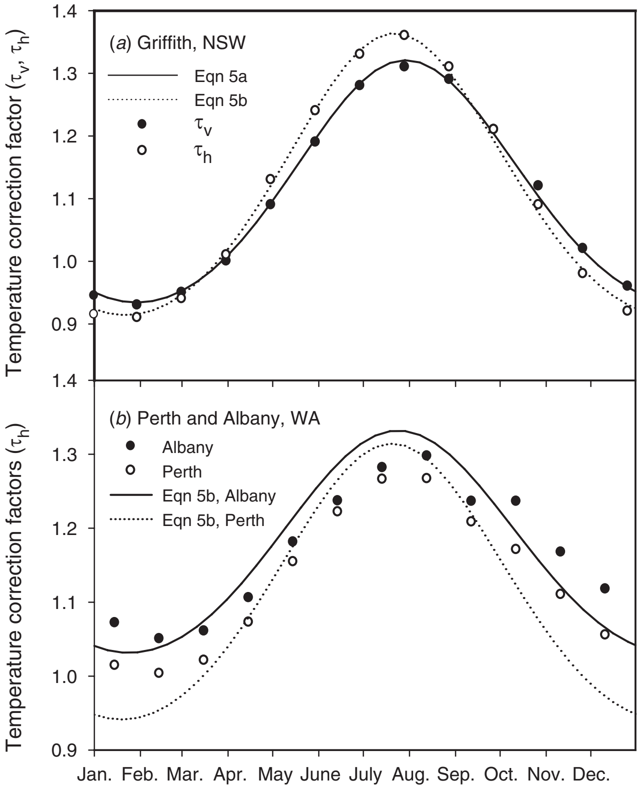

Fig. 2. Comparison of temperature corrections factors calculated using the proposed method *v.* those employed by (*a*) Slavich and Petterson (1990) and (*b*) Bennett and George (1995).

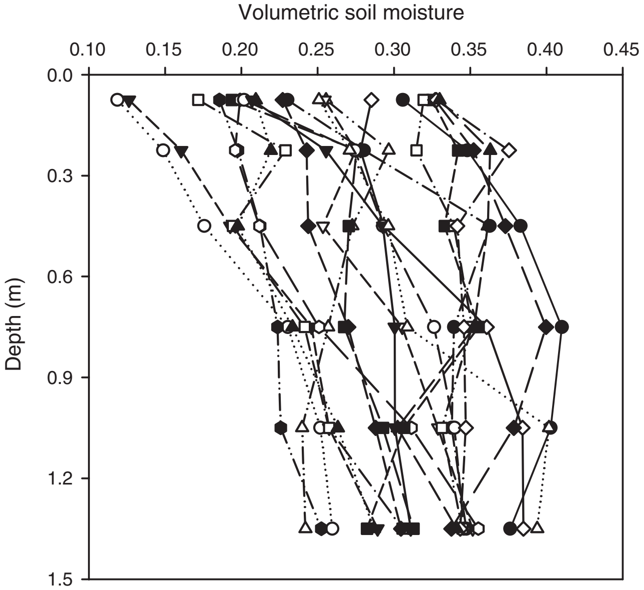

Fig. 3. A demonstration of the profiles of volumetric soil moisture used in conjunction with paired EM38 readings in order to prepare a calibration (Eqn 11).

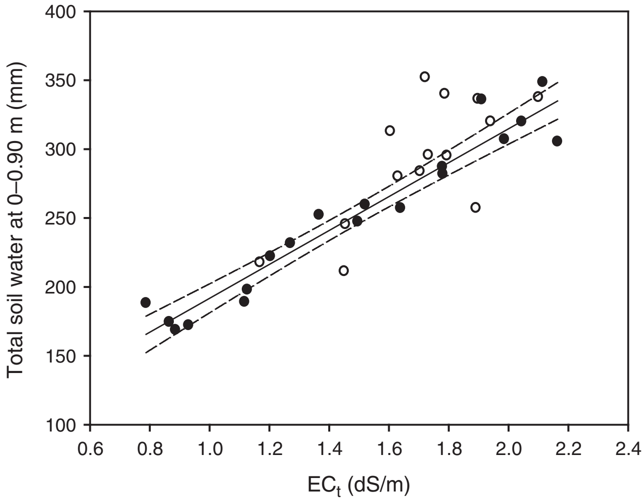

Fig. 4. Relationship between measured total soil water in the surface 0.9 m and EC_t (Eqn 3). The line of best fit (solid) is $y = 68.7 + 123.1x$ ($R^2 = 0.93$, s.e. = 15.3 mm). The 95% confidence interval is shown (broken line). Solid symbols show data used to perform the calibration and open symbols show data from neighbouring areas indicating differences due to soil variability or previous site management practices.

an area of somewhat uniform soil for use in this study. While many of the data from neighbouring areas fell along the calibration line, it must be reiterated that verification of this equation would be required for any nearby site, and it is unlikely to be appropriate to more distant sites. However, the methodology should be applicable for any other site with adequately uniform soil.

Once suitable temperature correction and calibration procedures had been identified the measured transects of EC_v and EC_h were easily converted into estimates of the spatial variation in SW_{90}. The effectiveness of these procedures are once again supported when the nature of the results are investigated in detail. To illustrate this, Fig. 5 shows the values of EC_v, EC_h, and SW_{90} for transects measured away from the trees over the 2004–2005 summer fallow period at approximately 90-day intervals. A perusal of the figure can uncover behaviour in the results that fosters further confidence in the approach. For example, the range in water contents predicted in the transect data agree with previously published data for soils in the area. Dalgliesh and Foale (1998) found a drained upper limit and cotton lower limit of plant extractable soil water of 358 and 204 mm, respectively, for the top 0.9 m of the soil profile. Given the predominantly dry conditions during the study, these values compare well with the range of soil water contents determined using EMI. We also see that although seasonal soil temperatures may create some variation in EMI measurements, the temperature correction and calibration bring subsequent estimates of the dry region next to the trees back to the observed lower-limit of soil water extraction in the first 15 m in the transects. Similary, while the story of open paddock soil moisture storage during the fallow is not readily identifiable in the raw EC_v or EC_h numbers, the resultant estimates of SW_{90} show a clear wetting up of the soil profile over the summer fallow period.

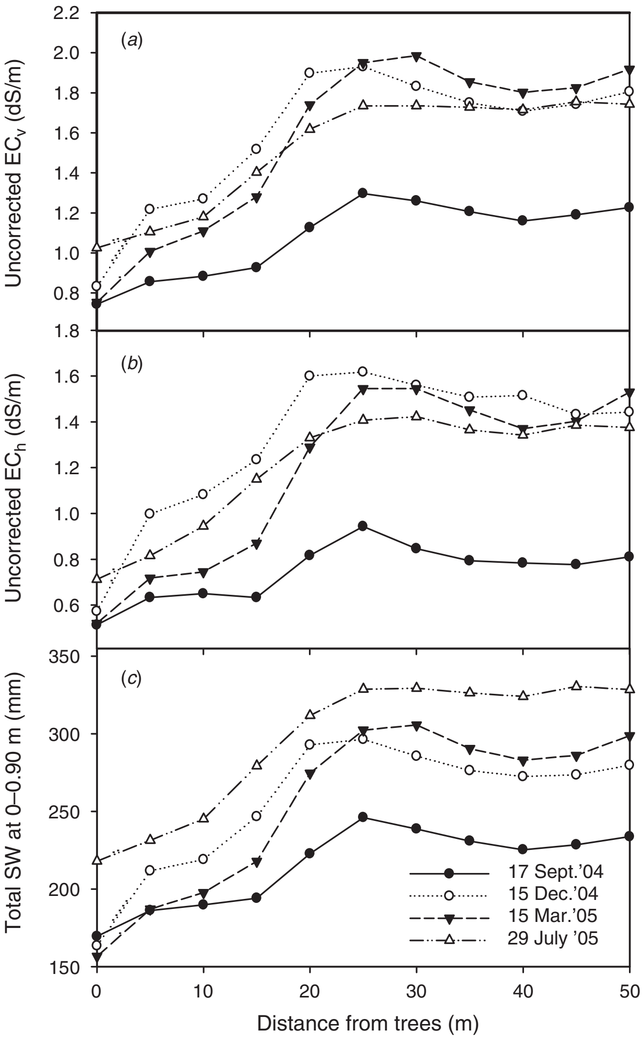

Fig. 5. Transects of (*a*) uncorrected EC_v (Eqn 1a), (*b*) uncorrected EC_h (Eqn 1b), and (*c*) soil moisture at ~90 day intervals during 2004–2005 to a distance of 50 m from the trees for a summer fallow field.

Finally, the ability of the technique to allow the researcher to investigate spatial patterns at a high resolution is demonstrated in the data collected during the cotton crop of the 2004–2005 summer. As described earlier, a skip-row configuration was used and measurements were required at 2-m intervals along each transect instead of the 5-m spacing used throughout the rest of the study. Figure 6 shows some of the results from this part of our study. Note how the similarity of neighbouring measurements indicates that noise inherent in the measurement method must be considerably lower than variation in the soil itself. The influence of cotton planting geometry and the resultant soil water extraction is also evident during the time-series of measurements. Early in the season, variation in soil moisture due to the placement of cotton plants is low as the plants establish themselves. By January, however, the EMI measurements taken in the horizontal dipole indicate considerable oscillation between the planted rows and the 'skips' (or non-planted rows). The lack of a similar pattern in the readings taken in the vertical dipole indicate that near-surface extraction of water by the cotton has taken place in the planted area only, resulting in a large amount of variability in soil moisture content both horizontally and vertically. By the end of the growing season the variation between planted and non-planted rows had disappeared, indicating that the crop had managed to extract most of the water between the planted rows. These results are similar to those shown by Routley *et al.* (2003) for sorghum.

Discussion and conclusions

The analysis above has indicated the effectiveness of EMI techniques in monitoring variation in soil moisture in response to its extraction by crops and trees in an agroforestry system. The technique allows for a greater degree of flexibility in terms of spatial and temporal resolution of sampling in situations where precise knowledge of the vertical distribution of soil moisture is not as important as its variation in time and space.

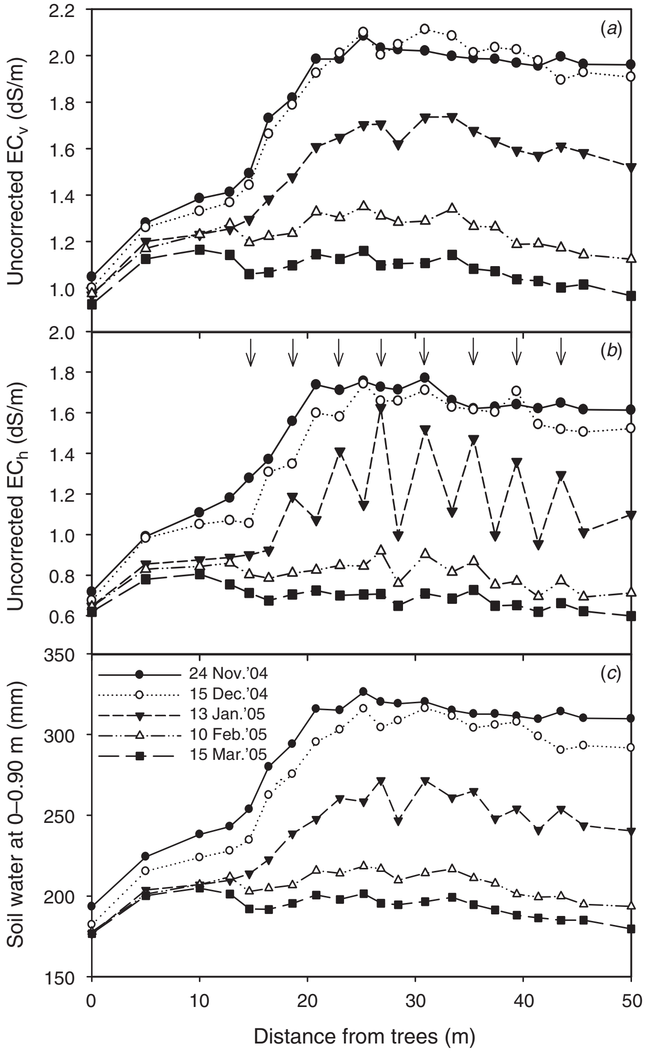

Fig. 6. Transects of (*a*) uncorrected EC_v (Eqn 1a), (*b*) uncorrected EC_h (Eqn 1b), and (*c*) soil water at approximately 30-day intervals during 2004–2005 to a distance of 50 m from the trees for a summer cotton crop. Arrows indicate the position of 'skipped' rows.

In the current study, >1500 measurements were taken over a 1.5-year period. Such a measurement regime would have been difficult with traditional approaches such as neutron scattering or gravimetric measurements. It is possible that even greater spatial resolution could be achieved using the extensive EMI mapping approaches as applied in precision agriculture (Corwin and Plant 2005). However, in this case, monitoring within a growing crop precluded the use of vehicular-based sampling. Moreover, manual sampling allowed the use of paired EC_v and EC_h readings at exactly the same point in space on the soil surface and the resultant use of linear combinations of these to create a density function that was more appropriate for the depth of the profile under investigation. It should be noted that the manufacturer of the EM38 does provide a version of the apparatus for instantaneous measures in both horizontal and vertical dipoles.

While the detailed nature of the results will be discussed in conjunction with other crop and tree data in later publications, the data shown above indicate that the technique developed here provided adequate detail and precision for use in the study of agroforestry systems. The nature of the soil water extraction patterns by the trees within the cropping area was clearly identifiable and quantifiable and so the results

Fig. 7. Locations of sites across eastern Australia for which representative temperature correction factors have been provided (see Table 2).

Table 2. Example temperature correction factors calculated for a range of locations in eastern Australia

Day of year	Charleville	Biloela	Narayen	Dalby	Warwick	Moree	Gunnedah	Condobolin	Griffith
				Vertical dipole					
1	0.86	0.92	0.91	0.99	0.98	0.93	0.98	0.95	0.95
30	0.85	0.91	0.90	0.97	0.97	0.91	0.96	0.93	0.93
60	0.86	0.92	0.92	0.99	0.99	0.93	0.98	0.94	0.95
90	0.91	0.95	0.97	1.02	1.03	0.98	1.03	0.99	1.01
120	0.97	1.00	1.04	1.08	1.10	1.06	1.10	1.08	1.09
150	1.05	1.06	1.11	1.14	1.18	1.15	1.19	1.18	1.20
180	1.12	1.12	1.17	1.19	1.24	1.23	1.26	1.27	1.28
210	1.15	1.15	1.18	1.21	1.26	1.27	1.28	1.31	1.32
240	1.12	1.14	1.15	1.19	1.24	1.24	1.26	1.29	1.29
270	1.06	1.09	1.09	1.14	1.18	1.16	1.19	1.20	1.20
300	0.98	1.03	1.01	1.08	1.10	1.07	1.11	1.10	1.10
330	0.92	0.97	0.95	1.03	1.04	0.99	1.03	1.02	1.02
360	0.87	0.93	0.91	0.99	0.99	0.94	0.98	0.96	0.96
				Horizontal dipole					
1	0.84	0.90	0.90	0.97	0.96	0.90	0.96	0.91	0.92
30	0.83	0.89	0.89	0.96	0.96	0.90	0.95	0.90	0.92
60	0.86	0.91	0.92	0.98	0.98	0.92	0.98	0.93	0.95
90	0.91	0.96	0.98	1.03	1.04	0.99	1.04	1.00	1.02
120	1.00	1.03	1.05	1.09	1.12	1.09	1.13	1.11	1.12
150	1.09	1.10	1.13	1.16	1.21	1.20	1.22	1.24	1.24
180	1.16	1.16	1.19	1.22	1.27	1.28	1.29	1.34	1.34
210	1.18	1.18	1.20	1.23	1.29	1.31	1.31	1.37	1.36
240	1.13	1.15	1.16	1.20	1.25	1.25	1.27	1.31	1.30
270	1.05	1.08	1.08	1.14	1.17	1.15	1.18	1.19	1.19
300	0.96	1.01	1.00	1.07	1.08	1.05	1.08	1.07	1.08
330	0.89	0.95	0.94	1.01	1.01	0.96	1.01	0.98	0.99
360	0.85	0.90	0.90	0.97	0.97	0.91	0.96	0.92	0.93

can be easily used in simulation or statistical studies. The ease of use of the instrument in the field, combined with a high resolution spatial capability, enables the researcher to overcome the constraints found in other methods of soil water monitoring.

The importance of an appropriate correction procedure for seasonal variation in soil temperature has been clearly demonstrated. The evaluation of a technique to account for this was undertaken for this study and for the previous work of Slavich and Petterson (1990). Only a small amount of information regarding the annual variation in soil temperatures was found to be necessary to develop an effective correction factor for EM readings in either dipole, for any given day of the year. Such data exists for many of the major agricultural regions within Australia. In order to illustrate the simplicity with which temperature corrections can be developed, soil temperature data for a series of locations across Queensland and New South Wales (Fig. 7) has been collated and used to derive a suite of correction factors spanning the annual cycle (Table 2). This demonstrates that even though the variation across this latitudinal series can be considerable, the approach used in the case study above can be employed with ease.

Many of the EMI approaches used to determine EC_a–depth profiles (e.g. Slavich 1990; Cook and Walker 1992) could possibly be used to determine the vertical distribution of soil moisture within the profile. In this study, EC_v and EC_h in the calibration data were highly correlated, and hence little information could be deduced from their comparison. This might reflect the shape of the profiles used or perhaps an insufficient difference in the density functions for the horizontal and vertical dipole measurements for the EM38. Perhaps other EMI apparatus which allow for a variation in inter-coil spacing might provide greater scope for detecting vertical variation in EC_a as suggested by Cook and Walker (1992). However, the significant variation between EC_v and EC_h for the skip-row cotton suggests that conditions might exist where the 2 density functions provided by the EM38 may be sufficient to allow an analysis of the variation of EC_a with depth.

Acknowledgments

The authors wish to thank Geoff and Wade Bidstrup for allowing us to collect data on their farms.

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Manuscript received 20 July 2006, accepted 9 December 2006