MEASURING MULTI-DEPTH SOIL MOISTURE CONTENT IN A VERTISOL SOILS WITH EM38

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ABSTRACT

Over the years, electromagnetic induction sensors, such as EM38, have been used to monitor soil salinity or local electrical conductivity (EC_a) and their output has been instrumented in establishing models for depth profiling of EC_a. In the previous work both the forward propagation and inverse matrix approaches offered potential to produce depth profiles of soil EC_a. However, it remains a question whether EM38 is able to measure θ_v in different depths. Earlier study has demonstrated that θ_v is a key driver of EC_a in deep Vertisol soils. Therefore, the objective of this study was to investigate the ability of the EM38 sensor to estimate vertical variations in the soil moisture profile using both the forward propagation models. The EM38 was calibrated to determine θ_v using detailed pit sampling and analysis. Before digging the pit, the EM38 readings (EC_a) at specified heights were taken in both vertical and horizontal dipole orientations from the same places where core samples were taken. All EC_a values were then converted to the local moisture-driven $EC_{a\theta}$. The forward-propagation models of Rhoades and Corwin (1981) [*Soil Sci. Soc. Am. J. 45: 255-260*] and Slavich (1990) [*Aust. J. Soil Res. 28: 443 - 352*] were refined and tested to see how well they could directly predict the vertical profile of soil moisture content. The relationship between θ_v and both EC_a & $EC_{a\theta}$ for all depth groups was statistically significant for both the Slavich model and Rhoades and Corwin model. However, the Slavich model, incorporating both vertical and horizontal dipole configurations, produced the best predictions with an error of approximately 10%.

Keywords: Soil moisture, EM38, depth profiling

INTRODUCTION

To meet the demand of precision agriculture, there has been growing interest in using electromagnetic induction (EMI) techniques to measure, monitor and map various soil attributes, soil moisture in particular. Although the θ_v of the soil profile at certain depths has been determined using EMI by several authors (eg. Kachanoski et. al. 1988; Reedy and Scanlon 2003), the depth specific moisture content of profiles has been left unexamined.

As the response of the EMI instrument varies with soil depth (McNeill 1980), it was assumed that the distribution of the soil attributes with depth could also be quantified successfully. This assumption proved sound and the depth response function of the EM38, when used to determine the θ_v in the deep Vertosol soils of this field site, has been shown to be stable (Hossain 2008). On the basis that θ_v remains the dominant factor in the response of the EM38 (assuming ions etc are all mobilized by θ_v), and that the depth response function is stable and known, then the depth response function of the EM38 could, in principle, be used to extract the depth profile of θ_v.

Given that the range of the EMI meter diminishes with depth, the vertical distribution of electrical conductivity of the soil profile could be predicted from a succession of EMI measurements at different heights above the soil surface (Rhoades and Corwin 1981). Empirical linear models have been used by many authors (eg. Rhoades and Corwin 1981; Slavich 1990) to convert measurements into EC_a depth profiles in what can collectively be termed ‘forward propagation’ (FP) models.

A ‘multiple regression coefficient model’, defined as FP model, was developed by Rhoades and Corwin (1981) to predict the EC_a in 0.3 m steps to a depth of 1.2 m. In their study, they regressed multi-height EMI measurements with EC_a measured by a four-electrode probe at different depths. The resulting regression equations allowed them to reconstruct the EC_a depth profile from multi-height EMI measurement in both horizontal and vertical dipole configurations, yielding a precise measurement ($R^2 = 0.99$) for all depth groups. A ‘modeled coefficient approach’ for predicting EC_a of composite depth profile of 0.05 m intervals was developed by Slavich (1990). In this model, a relationship between a simulated EC_a profile and calculated $EC_{a\text{-}V}$ and $EC_{a\text{-}H}$ readings was established. The simulated EC_a profile was generated from different mean EC_a values to create possible field EC_a profiles at 0.05 m intervals using a simulation process involving a cubic spline interpolation method. The objective of this study was to demonstrate the use of the forward propagation models to determine θ_v at depth.

THEORY

EM38 depth response and depth profiling

A key assumption in understanding the nature of the integrated response of the surface measurement of EMI instruments like the EM38 is that individual, below ground, horizontal ‘current loops’ do not interact (McNeill 1980). Consequently, the net secondary magnetic field at the receiver is the sum of the independent secondary magnetic fields from each of the individual current loops. This gives rise to the notional depth-response of the EMI sensor according to the relative contributions of secondary magnetic fields arising from different depths *directly* below the sensor. For vertical and horizontal dipole configurations (Kaufman 1983 after McNeill 1980), these contributions are given respectively as

$$\varphi^V(z) = \frac{4z}{(4z^2+1)^{3/2}} \qquad (1)$$

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

Here z is the ratio of axial distance below the sensor, z, and inter-coil spacing, s (1 m). Both of these expressions, shown graphically in numerous references (McNeil 1980; Lamb *et. al.* 2005; Morris 2009) are developed from the notion that the sensor is placed, regardless of vertical or horizontal dipole mode of operation, on the surface of a conductive half-layer, whereby there is no conductive medium above the surface ($z > 0$) and a conductive medium below the surface ($z < 0$). That is the EMI instrument is placed on top of the ground surface, in air.

Since the EC_a measured by the EM38 on the ground in either dipole configuration is a reflection of the integrated depth-response of the EM38, the cumulative response curve of both dipole orientations of the instrument can be determined by integrating Equations 1 and 2 with respect to depth (z). The cumulative response function for vertical and horizontal dipole configurations are therefore given by

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

and

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

where, $R^{V}(z)$ and $R^{H}(z)$ are cumulative response of the EMI instrument in depths for vertical and horizontal orientations respectively. These functions are plotted in Figure 1.

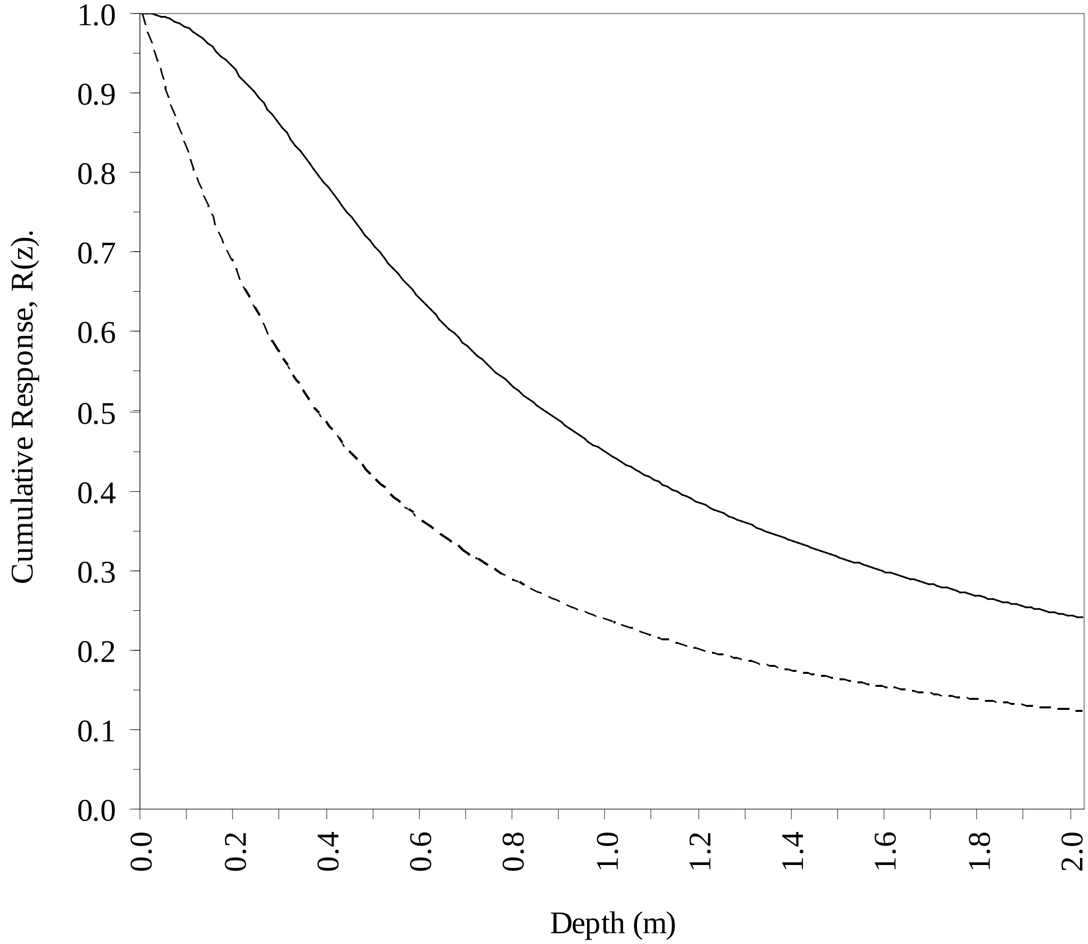

Figure 1 Cumulative responses of EM38 of all soil electrical conductivity at different depths for the vertical (—) and horizontal (---) dipole configurations. Curves calculated from McNeill (1980).

Recalling the key assumption of McNeill (1980), that the medium below the sensor is homogenous and of low induction number (N_B <<1), the secondary magnetic field is a very simple (and linear) function of soil electrical conductivity. Also, the linear model developed by McNeill (1980) was based on the assumption that the current flow within the horizontally stratified medium is entirely horizontal. Under these assumptions McNeill (1980) suggested that the sub-surface soil information at discrete depths could be determined by conducting measurements with the instrument at different heights. Borchers *et al.* (1997) discussed and improved the initial model, suggesting that if the instrument is held at a given height h above the surface, the apparent conductivity reading in both vertical and horizontal dipole configurations takes the form

$$EC_{a\text{-}V,H} = \int_0^{\infty} \varphi^{V,H}(z+h)\ EC(z)dz \qquad (5)$$

where, $EC_{a\text{-}V,H}$ is the apparent electrical conductivity measured by the EMI instrument, h represents the height of the instrument placed above the ground,

$EC(z)$ is the conductivity at depth z and $\varphi^{V,H}$ are, respectively the relative contributions of the sensitivity function of the vertical and horizontal the instrument in vertical and horizontal dipole configurations (Equations 1 and 2).

The forward propagation model of Rhoades & Corwin (1981) for EC_a depth-profile was based on the following equations.

$$EC_{0.-0.3} = \alpha_1 EC_{a1} + \alpha_2 EC_{a2} + \alpha_3 EC_{a3} + \alpha_4 EC_{a4} \tag{6}$$

$$EC_{0.3\text{-}0.6} = \alpha_1 EC_{a1} + \alpha_2 EC_{a2} + \alpha_3 EC_{a3} + \alpha_4 EC_{a4} \tag{7}$$

$$EC_{0.6\text{-}0.9} = \alpha_1 EC_{a1} + \alpha_2 EC_{a2} + \alpha_3 EC_{a3} + \alpha_4 EC_{a4} \tag{8}$$

$$EC_{0.9\text{-}1.2} = \alpha_1 EC_{a1} + \alpha_2 EC_{a2} + \alpha_3 EC_{a3} + \alpha_4 EC_{a4} \tag{9}$$

where subscripts 0-0.3, 0.3-0.6, 0.6-0.9, 0.9-1.2 represent the electrical conductivity of respective depths in metres, EC_{a1}, EC_{a2}, EC_{a3} and EC_{a4} represent the apparent electrical conductivity measured by the EM38 at 0, 0.3, 0.6, 0.9 and 1.2 m height above the surface and α_1, α_2, α_3, α_4 are the regression coefficients.

The Slavich (1990) model for reconstructing the EC_a profile is

$$EC_{a(0\text{-}z)} = \alpha_1 EC_{a\text{-}V} + \alpha_2 EC_{a\text{-}H} + c \tag{10}$$

where $EC_{a(0\text{-}z)}$ is the electrical conductivity of the particular depth, $EC_{a\text{-}V}$ and $EC_{a\text{-}H}$ are the vertical and horizontal electrical conductivity calculated following Equations (11) and (12) and α_1, α_2 and c are the regression coefficients. $EC_{a\text{-}V}$ and $EC_{a\text{-}H}$ were derived using following equations.

$$EC_{a\text{-}V} = \sum_{i=1}^{Nv} ECa_i (R^V{}_i - R^V{}_{(i-1)}) \tag{11}$$

$$EC_{a\text{-}H} = \sum_{i=1}^{Nh} ECa_i (R^H{}_i - R^H{}_{(i-1)}) \tag{12}$$

where *Nv* and *Nh* are number of layers to measurement depths in vertical and horizontal dipole configurations respectively, ECa_i is the mean EC_a value of the synthetic profile of the particular soil segment in *i*th depth layer and $R^V{}_i$ & $R^H{}_i$ are the vertical and horizontal cumulative depth-response function for the *i*th depth layer (Figure 1).

MATERIALS AND METHODS

Study site

The experiment was conducted on a 1 ha block on Clarke's Farm, an experimental property located at the University of New England, Australia (S 30^o 31.7', E 151^o 37') with a Black Vertosol soil.

Soil sampling and θ_v determination

Soil samples were obtained for gravimetric determination of volumetric soil moisture content (θ_v, m^3/m^3) using extracted soil cores and from excavated pits. A soil pit was established at each of 2 artificially dry and 2 artificially wet plots (3m x 5 m), giving a total of 4 soil pits. At each pit, 3 ring samples (73 mm diameter and 36 mm depth) were collected initially from the topsoil (0.1 m). At depths of 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 m, 3 larger ring samples (99 mm diameter and 78 mm depth) were collected by first exposing each level using an excavator and then extracting the samples from each site. Average values of θ_v were calculated for 'specific depth' intervals of 0-0.4, 0.4-0.8, 0.8-1.2 m and for 'composite depths' of 0-0.4, 0-0.8 and 0-1.2 m.

EM38 data collection

The EM38 measurements of EC_a were acquired at heights of 0, 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 m above the pit sites. Each measurement was recorded as the average of 3 separate measurements (in the same visit) for each height for both horizontal and vertical dipole orientations. Measured EC_a values were converted to local moisture-driven EC_a noted as $EC_{a\theta}$ using following equations developed by Hossain (2008)

$$EC_{a\theta\text{-V}} = 0.018\ EC_{a\text{-V}} - 0.163 \qquad (13)$$

$$EC_{a\theta\text{-H}} = 0.028\ EC_{a\text{-H}} - 0.176 \qquad (14)$$

Forward Models of Rhoades and Corwin for depth-specific θ_v prediction

The forward propagation model of Rhoades and Corwin (1981) was applied to the pit calibration data. Both the multi-height EC_a and subsequently converted $EC_{a\theta}$ values were regressed with the volumetric moisture content at composite depth groups of 0-0.4, 0-0.8 and 0-1.2 m and successive depth groups of 0-0.4, 0.4-0.8 and 0.8-1.2 m. The model equations generated were

$$\overline{\theta}_{v(a-z)} = \alpha_1 EC_{a\theta\text{-V,H1}} + \alpha_2\ EC_{a\theta\text{ -V,H2}} + \alpha_3\ EC_{a\theta\text{ -V,H3}} + \alpha_4\ EC_{a\theta\text{ -V,H4}} \qquad (15)$$

and

$$\overline{\theta}_{v(a-z)} = \alpha_1 EC_{a\text{-V,H1}} + \alpha_2 EC_{a\text{-V,H2}} + \alpha_3 EC_{a\text{-V,H3}} + \alpha_4 EC_{a\text{-V,H4}} \qquad (16)$$

where $\overline{\theta}_{v(a-z)}$ is the average θ_v (0-0.4, 0-0.8, 0-1.2, 0.4-0.8, 0.8-1.2 m), $EC_{a\text{-}V,H1}$, $EC_{a\text{-}V,H2}$, $EC_{a\text{-}V,H3}$, $EC_{a\text{-}V,H4}$ are EM38 measurements and $EC_{a\theta\text{-}V,H1}$, $EC_{a\theta\text{-}V,H2}$, $EC_{a\theta\text{-}V,H3}$, $EC_{a\theta\text{-}V,H4}$ are the converted EM38 measurements using Equations (13) and (14) at 0, 0.4, 0.8, 1.2 m height respectively and α_1, α_2, α_3, α_4 are the regression coefficients. The multiple regression analyses for this model were conducted using the JMP statistical software.

Forward Models of Slavich for depth-specific θ_v prediction

The Slavich (1990) model equation was employed in two forms; one each to accommodate EC_a and $EC_{a\theta}$:

$$\overline{\theta}_{v(a-z)} = \alpha + \beta_1 EC_{a\text{-}V} + \beta_2 EC_{a\text{-}H} \tag{17}$$

$$\overline{\theta}_{v(a-z)} = \alpha + \beta_1 EC_{a\theta\text{-}V} + \beta_2 EC_{a\theta\ H} \tag{18}$$

where $\overline{\theta}_{v(a-z)}$ is the average θ_v down to a given depth group (0-0.4, 0-0.8, 0-1.2, 0.4-0.8, 0.8-1.2 m), α, β_1 and β_2 are the modeled coefficients, $EC_{a\text{-}V}$, $EC_{a\text{-}H}$ are the actual surface EM38 measurements for vertical and horizontal dipole configurations and $EC_{a\theta\text{-}V}$, $EC_{a\theta\text{-}H}$ are EC_a values converted using Equations (13) and (14) for the specific dipole configuration. Comparison of fitted regression lines analysis was performed using Statgraphics software.

RESULTS AND DISCUSSION

Rhoades and Corwin model calibration

The EC_a for both vertical and horizontal dipole orientations predicts moisture content at different depths with accuracy ranges from 0.014 m^3/m^3 to 0.028 m^3/m^3 (Table 1). In the vertical dipole orientation the highest precision (R^2 = 0.98) was acquired in top depth group (0 - 0.4 m). This is a direct result of the depth response function of the EM38, where in vertical mode, the maximum response occurs at ~ 0.4 m depth which decreases to zero at the surface and again decrease with increasing depth below ~ 0.4 m depth. In the case of horizontal dipole configuration measurements, higher precision was observed (R^2 = 0.97 to 0.98) in all depth groups. This is attributed to the fact that significantly more of the integrated response of the instrument occurs from the surface to a depth of 1.2 m in the horizontal dipole configuration (~80%) compared to vertical dipole configuration (~62%).

The results achieved using converted $EC_{a\theta}$ values (Table 2) were consistent with those derived using EC_a (Table 1).

Table 1 Multiple linear regression equations between θ_v layers and multi-height EC_a measurements. All equations are statistically-significant ($p < 0.05$). Coefficients apply to $\overline{\theta}_{v(a-z)} = a + b_1EC_{a0} + b_2EC_{a0.4} + b_3EC_{a0.8} + b_4EC_{a1.2}$, where $\overline{\theta}_{v(a-z)}$ is the average volumetric moisture content at a given depth group.

Dipole Config.	Depth (m)	Regression equations coefficients: a	b_1	b_2	b_3	b_4	R^2	RMSE (m^3/m^3)
		Composite depths						
Horizontal	0-0.4	0.215	-0.001	0.023	-0.028	0.005	0.98	0.023
	0-0.8	0.344	0.004	-0.003	-0.002	-0.003	0.98	0.022
	0-1.2	0.389	0.007	-0.019	0.018	-0.007	0.98	0.017
		Specific depth						
	0-0.4	0.215	-0.001	0.023	-0.028	0.005	0.98	0.023
	0.4-0.8	0.473	0.010	-0.029	0.025	-0.011	0.97	0.021
	0.8-1.2	0.348	0.005	-0.020	0.023	0.004	0.97	0.014
		Composite depths						
Vertical	0-0.4	0.206	-0.015	0.019	0.069	-0.085	0.98	0.024
	0-0.8	0.253	-0.011	0.011	0.060	-0.071	0.97	0.025
	0-1.2	0.243	-0.005	0.003	0.045	-0.048	0.97	0.021
		Specific depth						
	0-0.4	0.206	-0.015	0.019	0.069	-0.085	0.98	0.024
	0.4-0.8	0.300	-0.007	0.004	0.052	-0.057	0.94	0.028
	0.8-1.2	0.222	0.005	-0.013	0.015	-0.002	0.89	0.024

Table 2 Multiple linear regression equations between θ_v layers and multi-height EC_a measurements subsequently converted to $EC_{a\theta}$. All equations are statistically-significant ($p < 0.05$). Coefficients apply to $\overline{\theta}_{v(a-z)} = a + b_1EC_{a\theta 0} + b_2EC_{a\theta 0.4} + b_3EC_{a\theta 0.8} + b_4EC_{a\theta 1.2}$, where $\overline{\theta}_{v(a-z)}$ is the average volumetric moisture content at a given depth group.

Dipole Config.	Depth (m)	Regression equations coefficients: a	b_1	b_2	b_3	b_4	R^2	RMSE (m^3/m^3)
		Composite depths						
Horizontal	0-0.4	0.268	-0.123	1.195	-1.846	0.828	0.99	0.012
	0-0.8	0.33	-0.036	0.703	-1.225	0.628	0.99	0.015
	0-1.2	0.355	0.023	0.251	-0.546	0.457	0.98	0.017

		Specific depth						
	0-0.4	0.268	-0.123	1.195	-1.846	0.828	0.99	0.012
	0.4-0.8	0.392	0.051	0.209	-0.602	0.431	0.97	0.022
	0.8-1.2	0.404	0.14	-0.65	0.813	0.109	0.89	0.025
		Composite depths						
Vertical	0-0.4	0.271	0.301	0.27	0.043	-1.416	0.93	0.050
	0-0.8	0.319	0.22	0.306	-0.144	-0.973	0.93	0.040
	0-1.2	0.306	0.117	0.308	-0.239	-0.422	0.95	0.026
		Specific depth						
	0-0.4	0.271	0.301	0.27	0.043	-1.416	0.93	0.050
	0.4-0.8	0.367	0.139	0.342	-0.332	-0.529	0.94	0.030
	0.8-1.2	0.279	-0.087	0.311	-0.429	0.679	0.99	0.003

Slavich model calibration

The calibration outcomes for the Slavich Model using both ECa and converted ECaθ measurements are summarized in Tables 3 and 4, respectively.

Using EC_a data, the precision of the model was found to be similar for each depth group except the lowest depth group (0.8 – 1.2 m). The highest accuracy of calibration (0.011 m^3/m^3) was found at the 0 – 0.4 m depth groups with highest precision (R^2 = 0.99). On the other hand the lowest precision and accuracy was associated with 0.8 – 1.2 m depth group with R^2 = 0.86 and RMSE = 0.027 m^3/m^3 respectively. Consistently strong relationships between θ_v and $EC_{a\theta}$ was also observed for all cases of composite depths (R^2 = 0.97 to 0.99) and for specific depth groups (R^2 = 0.78 to 0.99). The comparatively low R^2 value (0.78) was associated with 0.8-1.2 m depth group and with RMSE value of 0.027 m^3/m^3.

The Slavich model predicted θ_v very well for both composite and specific depth groups. The performance of this model was found to be similar to the original model developed by Slavich (1990) when applied to EC_a. This is possibly due to the ability of the model to incorporate both the vertical and horizontal measurements of EM38 which in fact encompasses the maximum soil volume to predict θ_v.

In both models a comparatively lower R^2 value was observed between θ_v at 0.8 – 1.2 m depth and apparent electrical conductivity (EC_a and $EC_{a\theta}$) of both dipole modes. This is not surprising since only 15% and 9% of the instrument's response in vertical and horizontal modes respectively comes from this depth segment.

Table 3 The regression coefficients for the average volumetric moisture content at particular depths, $\overline{\theta}_{v(a-z)}$ and EC_a measurements. Equation: $\overline{\theta}_{v(a-z)}$ = a + b_1 EC_{a-V} + b_2 EC_{a-H}. All results were statistically highly significant ($p < 0.0001$).

Depth (m)	a	b_1	b_2	R^2	RMSE (m^3/m^3)	N
			Composite Depths			
0-0.1	0.331	-0.004	0.006	0.99	0.015	8
0-0.2	0.370	-0.004	0.006	0.99	0.013	8
0-0.4	0.376	-0.003	0.005	0.99	0.011	8
0-0.6	0.384	-0.002	0.004	0.99	0.011	8
0-0.8	0.387	-0.002	0.004	0.99	0.014	8
0-1.0	0.352	-0.001	0.003	0.98	0.014	8
0-1.2	0.310	0.0003	0.002	0.97	0.014	8
			Specific Depth			
0-0.4	0.376	-0.003	0.005	0.99	0.011	8
0.4-0.8	0.396	-0.001	0.003	0.96	0.018	8
0.8-1.2	0.224	0.004	-0.001	0.86	0.022	8

Table 4 The regression coefficients for the average volumetric moisture content at particular depths, $\overline{\theta}_{v(a-z)}$ and EC_a measurements. Equation: $\overline{\theta}_{v(a-z)}$ = a + b_1 $EC_{a\theta-V}$ + b_2 $EC_{a\theta-H}$. All results were statistically highly significant ($p < 0.0001$).

Depth (m)	a	b_1	b_2	R^2	RMSE (m^3/m^3)	N
			Composite Depths			
0-0.1	0.335	-0.212	0.224	0.99	0.016	8
0-0.2	0.369	-0.191	0.202	0.99	0.015	8
0-0.4	0.380	-0.156	0.176	0.99	0.011	8
0-0.6	0.390	-0.133	0.157	0.99	0.012	8
0-0.8	0.396	-0.106	0.135	0.99	0.012	8
0-1.0	0.368	-0.050	0.101	0.98	0.012	8
0-1.2	0.331	0.009	0.067	0.97	0.014	8
			Specific Depth			
0-0.4	0.380	-0.157	0.176	0.99	0.011	8
0.4-0.8	0.410	-0.064	0.101	0.97	0.016	8
0.8-1.2	0.263	0.176	-0.037	0.78	0.027	8

CONCLUSION

The results of this study confirm that the depth profile of volumetric moisture content can be constructed from on-ground or multi-height EM38 measurements using forward propagation models. There is no significant difference in the ability to predict θ_v using EC_a or $EC_{a\theta}$ values; thus direct measurements of EC_a can be used without converting it to $EC_{a\theta}$. Results of this study show that two forward propagation models can be applied to reconstruct the depth profile of θ_v with accuracies (as determined by RMSE) of approximately 10%.

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