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Mapping soil moisture across an irrigated field using electromagnetic conductivity imaging

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ABSTRACT

The ability to measure and map volumetric soil water (θ) quickly and accurately is important in irrigated agriculture. However, the traditional approach of using thermogravimetric moisture (w) and converting this to θ using measurements of bulk density (ρ—cm^3/cm^3) is laborious and time consuming. To speed up the process electromagnetic (EM) instruments have been used to assist in mapping average θ along a transect or across a field. This is because the apparent soil electrical conductivity (EC_a) measured by EM instruments has been shown to be a function of θ, when other soil properties are uniform. However, mapping depth-specific soil θ has been little explored. One possible approach is to invert the EC_a data to calculate estimates of true electrical conductivity (σ) at specific depths (i.e., 0.15, 0.45, 0.75, 1.05 and 1.35 m) and couple this to measured θ. This research explores this possibility by using a single frequency multi-coil DUALEM-421 across a centre-pivot irrigated Lucerne field (*Medicago sativa* L.) in San Jacinto, CA, USA. The first aim is to determine an optimal set of inversion parameters (i.e., forward modelling, inversion algorithm and damping factor—λ) which are appropriate to establish a calibration between σ and θ. In this regard the largest coefficient of determination (R^2 = 0.56) is achieved when we used the FS model, S2 algorithm and a λ = 0.3. The second aim is to see if all the coil arrays of the DUALEM-421 are necessary. We conclude that while the DUALEM-1 produces a larger R^2 (0.59), the use of the DUALEM-421 data is better (R^2 = 0.56), because the total model misfit (4.70 mSm^{-1}) is smaller and because it better accounts for the spatial variation of θ in the subsoil. In terms of predicting θ, the calibration equation ($\theta = 2.751 + 0.190 \times \sigma$) was examined using a leave-one-out cross validation. The Lin's concordance (0.73) between measured and predicted θ was good. The resulting 2-d depth slices and cross-sections gave insights into the spatial distribution of θ which allowed the inference of depth of saturated soil and location of the wetting front and identified areas where deep drainage may be problematic. The approach has applications for water use and management given it can identify inefficiencies in water application rates and use.

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1. Introduction

Although it represents a small percentage (~0.05%) of globally available freshwater (Dingman, 2002), soil moisture is a key store of water in the hydrologic cycle and is of importance to hydropedological (Dunne et al., 1975), biological (Rodriguez-Iturbe, 2000) and biogeochemical processes (White et al., 1997). Of equal significance is that agriculture is the largest user with approximately 70% of water use (Fischer et al., 2007) with nearly 40% of food supply coming from irrigation (FAO, 2002). Because of the transient nature of soil moisture, it is crucial that it be measured, so that its variation can be quickly determined over large areas and at various depths. This information can subsequently be used for applying irrigation water variably under precision irrigation scheduling (Hedley et al., 2010). The most accurate method is to determine wetness (w—g g^{-1}), which is time consuming, because: (i) it requires 24 h oven drying during which time field conditions change (Blonquist et al., 2006), and (ii) measurements of bulk density (ρ—cm^3 cm^{-3}) are necessary to enable estimation of volumetric moisture content (θ—g cm^{-3}).

To improve efficiency in measuring θ, several field instruments are commonly used, including time domain reflectometry (TDR) (Wraith et al., 2005) and neutron probes (Kodikara et al., 2013). Either way extrapolation over the field scale is difficult if soil type is unknown; given θ is influenced by texture and salinity. To improve efficiency in mapping θ, electromagnetic (EM) induction

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instruments can be used (Huth and Poulton, 2007). This is because the measured soil apparent electrical conductivity (EC_a) is a function of θ, salinity, organic matter content, bulk density (ρ), and texture (Corwin et al., 2003). If these other factors remain constant, differences in θ can be measured and mapped. Kachanoski et al. (1988) first demonstrated this potential when they calibrated average (0.5 m) θ measured using a TDR to EM38 EC_a. Subsequent work by Kachanoski et al. (1990) confirmed these results using neutron probe measured average (1.7 m) θ. More recently, Hedley et al. (2013) mapped average (0.5 m) θ across an irrigated field using EM38 EC_a, whilst Robinson et al. (2009) mapped θ at a depth of 0.4 m with time and across a small catchment.

Although successful results have been achieved for estimating and mapping average θ and available water content (e.g., Gooley et al., 2014), few studies have mapped θ at different depths and as a function of EC_a. One way to do this is to use multiple (i) EM instruments of varying coil spacing (i.e., using EM38 and EM31) and/or (ii) coil orientations (i.e., vertical and horizontal) and coupled with inversion software. This would be akin to using direct current resistivity instruments and res2dinv software (GeoTom Software, 2010), which when used in concert have been useful in inferring θ variation at various depths in irrigated (Kelly et al., 2011) and dryland (Schwartz et al., 2008) systems. One reason the approach has not been explored for EC_a data has been the lack of easy-to-use software. However, recent research has demonstrated that EM4Soil can be used to jointly invert single frequency EM38 and EM31 EC_a to map salinity (Triantafilis and Monteiro Santos, 2009; Huang et al., 2015) or using a single frequency and multiple coil arrayed DUALEM-421 to map exchangeable sodium percentage (Huang et al., 2014) and clay (Triantafilis et al., 2013).

In this research we aim to determine the ability of DUALEM-421 EC_a to develop electromagnetic conductivity images (EMCIs) using EM4Soil software and to establish a single linear-regression (LR) between calculated true electrical conductivity (σ) and θ at various depths. The first task is to determine a suitable inversion algorithm (e.g., full solution), forward modelling (e.g., S1) and damping factor (e.g., $\lambda = 0.3$). We then assess whether all coil arrays of the DUALEM-421 are necessary to predict θ. In doing this we also simulate and demonstrate the usefulness of single coil array instruments (i.e., DUALEM-1 or EM38) as well as dual array configurations (i.e., EM38 and EM31 or DUALEM41). We also see how the use of additional arrays assesses the non-uniqueness issue. Once an optimal set of coil arrays is determined we test how well we can predict soil θ across an irrigated Lucerne field near San Jacinto. We chose this crop and field because a recent report by the U.S Global Change Program (Georgakakos et al., 2014) projects annual precipitation to decrease in southwest U.S.A, making water an increasingly valuable resource and because more than 40,000 ha of Lucerne is grown in California; making the crop the largest user of irrigation water due to the amount grown and its long growing season (Hansen et al., 2008).

2. Materials and methods

2.1. Study site

The study field is located on Scott Brothers' Dairy Farm in Southern California's Riverside County (lat. 33°50′25.43″N, long. 117°00′14.93″W) approximately 9 km northwest from downtown San Jacinto (Fig. 1). The study field is 32 ha and is farmed with irrigated Lucerne (*Medicago sativa* L.), which is used for consumption on-farm in a dairy feed lot. Since the 6th of March 2008, dairy lagoon water has been used. The average properties of the water (between March 2008 and June 2009), indicate that the pH is slightly alkaline (pH 7.8) and slightly saline ($EC_{iw} = 1.63$ dS/m). Given the SARw is 4.3 the potential for water infiltration problems is unlikely (Ayers and Westcot, 1994), however (Corwin et al., 2010).

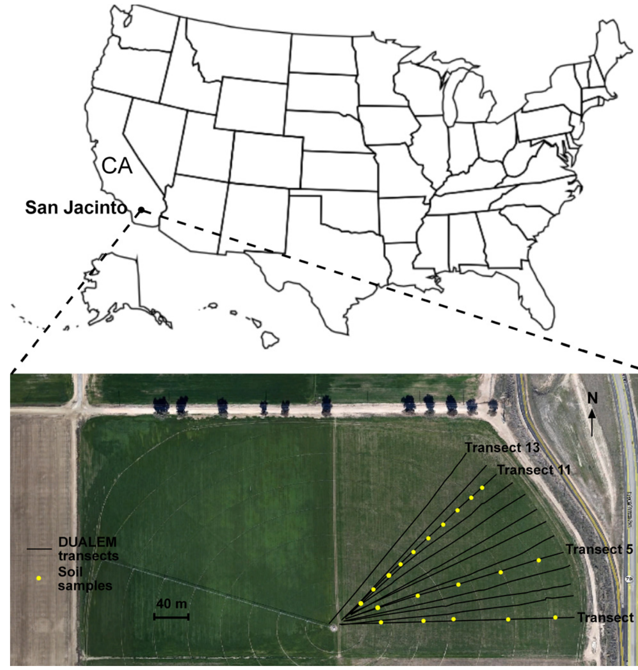

Fig. 1. Location of study area, EC_a transects and soil sampling locations on transects 1, 5 and 11.

2.2. DUALEM-421, data collection and interpolation

The DUALEM-421(DUALM Inc., Milton, ON, Canada) is a single-frequency (9.0 kHz) multi-coil arrayed (i.e., 6) EM instrument which operates at low induction numbers and consists of a transmitting coil (Tx) and three receiver coil (Rx) pairs. The Tx and one Rx pair have horizontal windings which form a horizontal coplanar array (HCP). The distances between the Tx to the coplanar Rx are 1, 2, and 4 m. The notation 1mHcon, 2mHcon, and 4mHcon represents EC_a and corresponds to measurements of approximately 0–1.5, 0–3.0, and 0–6.0 m, respectively. The other coils in each Rx pair have vertical windings and with the Tx forms perpendicular arrays (PRP). The distances between the Tx to the Rx are 1.1, 2.1, and 4.1 m, respectively. The respective EC_a measurements are represented by 1mPcon, 2mPcon, and 4mPcon with theoretical depth of corresponding to approximately 0–0.6, 0–1.2, and 0–2.4 m, respectively.

2.3. EC_a data, soil sampling and laboratory analysis

The field was irrigated on 28 August 2014. Immediately after this 13 transects (see Fig. 1) were traversed across the south-eastern quadrant with EC_a acquired with a DUALEM-421. The instrument was carried at a height of 0.2 m. Latitude and longitude was acquired via a Trimble Hurrican L1 antennae. The GPS and DUELAM-421 EC_a were logged using a Trimble GPS Pathfinder Pro Series Receiver.

To calibrate the inverted DUALEM-421 EC_a (i.e., σ), several calibration sites were selected. As shown in Fig. 1 these were located on three separate transects. On transects 1 and 5, 5 soil samples sites were selected. On transect 11, 10 sites were chosen. At all these sites, soil samples were collected at 0.3 m intervals to a depth of 1.5 m. Sampling was carried out on the same data the EC_a was acquired. All samples were sealed in plastic bags. In addition, undisturbed soil cores were obtained for bulk density determination (ρ—g cm^{-3}) but only along transect 5.

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