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Assessing field-scale soil water distribution with electromagnetic induction method

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SUMMARY

We evaluated the sensitivity of electromagnetic induction (EMI) method to variation in soil water in an irrigated cotton field by measuring apparent electrical conductivity (EC_a) with a Geonics EM38. EC_a was measured at a fixed position in each plot (within the furrow adjacent to stands of cotton planted on ridges) at ground level as well as at 0.1 and 0.4 m height above the ground. Measurements were made in both vertical and horizontal modes (VM and HM) of EM38 to allow soil water sensing within 1.5 and 0.75 m depths at each location. Surrogate values of soil water were obtained with a locally calibrated neutron probe adjacent to EM38 measurements.

All measurements were carried out within three replicate plots of four irrigation treatments at various times during cotton growth. As EC is sensitive to variation in temperature, soil and air temperature was also measured at the time of EM38 measurements. Temporal patterns of variation in EC_a and soil water were broadly similar for shallow and deep soil layers. Values of EC_a over the season increased nonlinearly with increased values of accumulated soil water within specific depths with high degree of confidence ($P \leqslant 0.001$) and high coefficient of determination (R^2) for fitted models. Although both soil and air temperature varied over the season (21.2–39.1 °C for soil and 26.1–33.2 °C for air), dependency of EC_a on temperature was weak. The relationship between EC_a and soil water was greatly affected by surface configuration in crop fields (i.e. whether the crop was planted on a flat bed or a raised bed) and season. Thus, there is a need to calibrate the EMI equipment to suit local condition in order to measure soil water distribution at field scale.

1. Introduction

Soil water is an important state variable in most hydrological investigations at field and catchment scales (Calamita et al., 2012; Minet et al., 2012). Spatial and temporal variability of soil water over a cropping season is an important determinant of yield variability (Wijewardana and Galagedara, 2010). Information on how available resources (e.g. water or nutrient) vary within a crop field over time is important to optimise crop growth and yield. There is always scope to conserve soil water or use it efficiently at field scale (Fereres and Soriano, 2007; Hsiao et al., 2007) from the knowledge of spatial and temporal distribution of soil water. Water requirement of crop plants in a field may vary spatially if there is a subtle variation in soil properties (e.g. texture or water-holding capacity). Soil water mapping may be used at field scale to accommodate such variation to implement distinct irrigation application zones (Hezarjaribi and Sourell, 2007).

Conventional methods of measuring and monitoring water content in a crop field is usually time consuming as it may involve a several point measurements requiring destructive soil sampling or use of radioactivity (e.g. neutron source) or using electromagnetic techniques with time-domain and frequency domain principles (Cook et al., 1992; Dalton, 1992). Absolute accuracy in soil water content measurements also requires soil-specific sensor calibration (Leib et al., 2003). All these make a soil water sampling plan for large crop fields extremely difficult. Therefore, reasonably accurate, fast, and inexpensive method for determining soil water over large area is needed to produce site-specific maps of available water at a resolution appropriate for precision agriculture (Akbar et al., 2005). Electromagnetic induction (EMI) method of measuring apparent electrical conductivity (EC_a) has received less attention for soil water mapping as it was developed to complement traditional soil surveys where part of the information includes spatial variation in soil moisture and texture (King and Dampney, 2000).

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EMI technique is commonly used to measure depth-weighted average EC of a soil column to a specific depth (termed as EC_a) by inducing an electrical current flow into the soil via a transmitter coil (McNeill, 1980a). These current sets up a secondary electromagnetic field (Tromp-van Meerveld and McDonnell, 2009) which can be converted into an output voltage that relates linearly to depth-weighted soil EC_a (Rhoades, 1992). EC_a measured in this way is affected by several key soil properties which include soil salinity (soluble salt content), amount of clay and clay mineralogy, soil moisture and temperature (Friedman, 2005; McNeill, 1980a). Information on soil salinity can usually be obtained by local calibration of specific EMI equipment. Lesch et al. (1995a,b) used a direct calibration approach with the EMI method to quantify within-field variations in soil salinity under uniform management and where water content, bulk density, and other soil properties were reasonably homogeneous. As EC_a is affected simultaneously by several soil properties, it is difficult to separate the effect of single soil property (e.g. soil water) on EC_a. However, in two separate studies, Kachanoski et al. (1988, 1990) found spatial variation in soil water stored within the top 0.5 and 1.7 m to be highly correlated with the spatial variation in EC_a measured with two EMI meters (i.e. Geonics EM38 and EM31). The operating frequency for the current models of these EMI meters are 14.5 and 9.8 kHz, respectively (Geonics Limited, Ontario, Canada, http://www.geonics.com/). Sheets and Hendrickx (1995) extended this approach to predict soil water content measured with a neutron probe from EC_a measured with an EM31 over a 1.95 km transect and were able to estimate soil water content with an approximate accuracy of 0.02 $m^3\,m^{-3}$. Despite the differences in operating frequency of EM31 and EM38 affecting their sensitivity, it has been possible to measure soil water and groundwater depth with reasonable accuracy on hill slopes of 2500 m^2 (Sherlock and McDonnell, 2003).

The behaviour of a soil–water sensor calibrated at a field site should not change over time within the field boundary. However, when soil–water response is derived via EC_a employing EMI technique, the calibration may be affected by seasonal variation in soil and air temperature (Reedy and Scanlon, 2003). In addition, the configuration of planting bed may also affect local calibration of EMI-based sensor due to the modification of soil physical properties within the planting bed (Lichter et al., 2008). Planting beds (e.g. flat or raised-bed) are often designed to alter spatial distribution of water and applied fertilizer to improve water and nutrient use efficiency of crops (Singh et al., 2010). Based on these considerations, this study is designed to determine if EMI technique would be useful in estimating soil water distribution in cotton fields with the complexity of raised bed planting. This issue will be addressed (also) by comparing the results of this work with a previous work (Padhi and Misra, 2011) conducted in wheat planted field on a flat bed configuration.

2. Materials and methods

2.1. Experimental strategy

All measurements were carried out at the same experimental field located in Queensland, Australia (27°30′44″S, 151°46′55″E, and 431 m elevation) as reported by Padhi and Misra (2011). The experiment was planted with cotton (*Gossypium hirsutum* L.). The soil at the experimental site was a self-mulching, black vertosol (Isbell, 1996) which contained 76% clay, 14% silt and 10% sand in the surface horizons. Other soil properties were as reported previously (Padhi and Misra, 2011).

Due to the small area used for the experiment (details given below), any spatial variation in soil properties within the experimental field was assumed to be small compared to the variation in soil water and temperature over the growing season of cotton. There were 12 plots within the experiment which were arranged following a randomised block design with three blocks (replicates) within which four irrigation treatments were randomly allocated. Each replicate plot had a dimension of 20 m × 13 m, which was separated from adjacent plots with 4 m wide buffer.

Irrigation treatments were identical to our previous study (Padhi and Misra, 2011) and were based on plant available water capacity (PAWC). PAWC is the difference between the upper water storage limit of the soil (similar to field capacity) and the lower extraction limit of a crop over the depth of rooting (similar to permanent wilting point). The upper and lower limits of PAWC were measured in the field prior to the current experiment using 10 replicate plots for which volumetric soil water content was measured at 0.1 m depth interval from surface to 1.5 m depth. Average values of PAWC for the experimental site were 371 and 394 mm within the potential rooting depths of 1.3 and 1.5 m, respectively. Irrigation treatments used for this experiment were: T50 – 50% depletion of PAWC, T60 – 60% depletion of PAWC, T70 – 70% of PAWC and T85 – 85% of PAWC. Using rainfall record and soil water values, irrigation was given to each treatment when the water content values reached the designated% of PAWC. For example, T50 plots were irrigated when PAWC was close to 197 mm (i.e. 50% of PAWC within 1.5 m depth). In this way, irrigation was scheduled for all the replicate plots of each treatment on the basis of soil water measured with a neutron probe in each plot (details given later) and rainfall recorded at the experimental site. Daily variation of temperature, rainfall and relative humidity for the experimental site (from an automatic weather station adjacent to the experimental site) for the cotton season is shown in Fig. 1.

2.2. Crop management

Cotton was planted at the centre of ridges (0.2 m high) with an inter-row spacing of 1 m on 15th November 2008. All plots received 68 kg N ha^{-1} of urea at the time of planting. For weed control, 1 L ha^{-1} of Glyphosate was initially applied on 24th November 2008 with a subsequent application of 1.5 L ha^{-1} on 15th January 2009. At 70 days after planting (DAP), an additional amount of N-fertilizer (102 kg N ha^{-1}) was applied. Each replicate plot was irrigated with bore water using a hand-shift sprinkler system. Partial-circle sprinkler heads were used to avoid irrigation of adjacent plots. Three rain gauges were installed in each plot to estimate the amount of water applied during irrigation. Since the amount of irrigation at a given time was small (ranging from 6 mm to 58 mm), there was little scope for runoff and drainage. Irrigation treatments in various plots were imposed on 67 DAP and

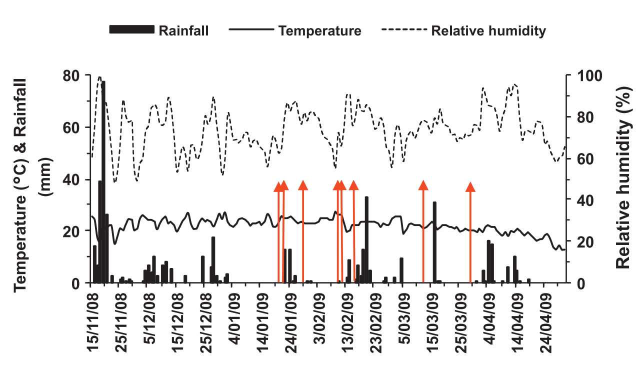

Fig. 1. Daily variation of air temperature, relative humidity and rainfall at the experimental site during the cotton season. Vertical arrows indicate timing of irrigation.