View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by University of Southern Queensland ePrints

Sensitivity of EM38 in determining soil water distribution in an irrigated wheat field

J. Padhi[a], R.K. Misra[a*]
[a]*Faculty of Engineering and Surveying, National Centre for Engineering in Agriculture and CRC for Irrigation Futures, University of Southern Queensland, Toowoomba, Queensland 4350, Australia*

Abstract

Geonics EM38 is a portable, non-invasive equipment that induces an electrical current in the soil for rapid measurement of apparent electrical conductivity (EC_a) in the field. We used an EM38 in a wheat field to evaluate the effects of systematic variation in soil water content (within three replicate plots of four irrigation treatments) and seasonal variation in soil temperature on EC_a. The effective depth of sensing of EM38 could be varied by using it in both vertical and horizontal dipole modes and by placing it at various heights above the ground. Accumulated water within various soil depths was measured with a neutron probe throughout the season. Values of EC_a over the season for a soil depth related linearly or nonlinearly with soil water within that depth with a coefficient of determination (R^2) of 0.70-0.81. EC_a values were also influenced by variation in soil temperature within 5-25 cm depth (range 10.1-29.3 °C) and air temperature (range 14.2-34.0 °C), but to a smaller extent than soil water. The overall relationship between EC_a, soil water and soil temperature improved considerably when multiple regression was used (R^2 = 0.82-0.98). Good correspondence between maps of EC_a and soil water content over the experimental field suggests that EC_a maps could be useful in determining spatial distribution of soil water within crop fields so that variable rather than uniform quantity of irrigation water can be applied to improve water use efficiency.

Keywords: Electromagnetic induction; EM38; Irrigation; Soil water content; Spatial variation; Water use efficiency

1. Introduction

Spatial variability in agricultural fields is one of many factors affecting the performance of most irrigation systems. Inefficient application and/or distribution of irrigation may reduce yield and quality of the crop when it is combined with inefficient use of fertilizer and other agricultural inputs reducing the overall water use efficiency (Sanders et al., 2000). Spatial variability in crop yield in a field may arise directly due to the variation in uptake and availability of water and nutrients to crop plants and indirectly due to within-field variation of water, nutrients, soil and landscape factors (soil texture, structure, depth, salinity, organic matter, slope and aspect) and micro weather conditions. Crop management factors such as competition from weeds, pesticide damage, inconsistent seed germination, lodging, and hail damage may also cause spatial variation in crop yield. Despite such a large number factors contributing to variation in yield, the single most important factor is the presence of too much or too little water in a crop field (McBride, 2003). In order to increase water use efficiency, there is a need to quantify spatio-temporal variability in crop yields within a field by robust methods to explain within-field variations in physical and chemical properties of soil - considered as crucial elements of precision agriculture (Bullock and Bullock, 2000). Increased interest in precision agriculture in recent years has led to a need for soil maps that are more detailed and accurate than those traditionally produced (Batte, 2000). Although intensive soil sampling is the most accurate way to quantify spatial variability in a field (Havlin et al., 1999), it is time consuming and expensive. More rapid and inexpensive methods are required to measure spatial variability of soil properties in the field.

* Corresponding author at: Faculty of Engineering and Surveying, University of Southern Queensland, Toowoomba, QLD 4350, Australia.
Tel: +61 7 4631 2805; Fax: +61 7 4631 2526
Email address: misrar@usq.edu.au

In-situ measurement of apparent electrical conductivity (EC_a) in the field has generated considerable interests over time due to its potential ability in quantifying spatial variability of soil because EC_a can be used as a surrogate variable to infer other soil properties. Electromagnetic induction (EMI) is a non-invasive technique that allows measurement of apparent soil electrical conductivity (EC_a) by inducing an electrical current in the soil (McNeil, 1980a). A fraction of the secondary, induced electromagnetic field when converted into an output voltage relates linearly to depth-weighted soil EC_a (Rhoades, 1992). EMI method is usually safer than other measurement methods as it does not require a radioactive source (e.g. use of a neutron source in a neutron moisture meter) and is considerably faster than other methods due to its greater portability and non-invasive characteristics (Reedy and Scanlon, 2003). Zhu et al. (2010) demonstrated that EMI surveys could be used for improved soil mapping of agricultural landscapes for repetitive monitoring of a large number of fallow and cropped sites.

In-situ measurements of EC_a with EM38 (based on the EMI technique) have received considerable interests from the precision agriculture community (Corwin and Lesch, 2005). Several soil properties correlate directly or indirectly with EC_a (Sudduth et al., 2005). The parameters which dominantly influence EC_a are soil salinity, clay content and clay mineralogy, soil moisture and soil temperature (Friedman, 2005; McNeill, 1980a). EC_a data can be used to indirectly estimate soil properties if the contributions of the other soil properties affecting the EC_a measurement are known or can be estimated. Good correlation has been found between clay content and soil electrical conductivity measurements with EM38 in previous studies (Hedley et al., 2004; Triantafilis and Lesch, 2005). This technique has been also used to study variations in salinity (Rhoades et al., 1989; Triantafilis et al., 2000) and the risk of deep drainage of water (Triantafilis et al., 2004). Spatial measurement of EC_a has been reported as a potential measurement for predicting variation in crop production caused by soil water differences (Heermann et al., 2000).

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 bulk soil electrical conductivity measured with EMI meters (i.e. EM38 and EM31). In contrast, Khakural et al. (1998) obtained relatively poor relationships between EC_a and moisture content for vertical and horizontal measurement modes of EM38. It appears that the relationship between soil water content and EC_a may be affected by other soil properties (e.g. soil texture or clay content).

Despite conflicting reports in studies mentioned above, EC_a has been found to be linearly related with soil moisture content in recent studies (Brevik et al., 2006). Soil water content is still considered to be the single most important of the four commonly cited factors (soluble salts, clay content and mineralogy, soil water content and soil temperature) affecting EC_a (Brevik and Fenton, 2002). The study reported here was conducted to identify: the combined effects of seasonal variation in soil water content and soil temperature on apparent electrical conductivity of soil (EC_a) measured with EM38 in both vertical and horizontal dipole modes; the effects of placing EM38 at various heights above the ground on EC_a and the role of EC_a maps in identifying soil water distribution within crop fields to assist precision irrigation.

2. Materials and Methods

2.1. Site description

This study was conducted in an experimental field with wheat (*Triticum aestivum* L.) at Agri-Science Queensland experimental station near Kingsthorpe (27°30'44"S, 151°46'55"E, and 431 m elevation), Queensland, Australia. Soil at this experimental site was a haplic, self-mulching, and black vertosol (Isbell, 1996). It is a self-mulching medium to heavy cracking clay soil with 76% clay, 14% silt and 10% sand in the surface horizons. The soil has an organic carbon content of 1.3%, pH 7.2, EC 35 mS m^{-1} and CEC 86 $cmol_c\ kg^{-1}$. The field bulk density of the soil was 1200 kg m^{-3}.

2.2. Experimental strategy

The sensitivity of EM38 to soil water content and other environmental variables (e.g. temperature) can be determined using an approach similar to calibration of soil water measuring instrument (e.g.

neutron probe). Although calibration of soil water devices can be made in large containers with reconstituted soil (e.g. experiments of Reedy and Scanlon, 2003), it is difficult to cover a wide range of soil/air temperature and soil water variation in the subsoil (within 0.5-1.0 m depth). Since agricultural crops can deplete soil water from both surface- and sub- soil and are usually grown over a season where natural variation in air and soil temperature occurs, all measurements were made within an irrigation experiment with wheat. 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 wheat.

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 (Fig. 1). Each replicate plot had a dimension of 20 m × 13 m, which was separated from adjacent plots with 4 m wide buffer. All irrigation treatments were based on plant available water capacity (PAWC) as defined below. Plant available water capacity (PAWC) is the difference between the upper water storage limit of the soil and the lower extraction limit of a crop over the depth of rooting (Gardner 1985). PAWC for the experimental field was based on two parameters: drained upper limit (DUL) as the upper water storage limit and crop lower limit (CLL) as the lower extraction limit over the depth of rooting (Ratliff et al., 1983; Ritchie, 1981). Both DUL and CLL were determined in 10 replicate plots of the experimental field at 0.1 m depth increments from the soil surface down to 1.5 m depth. Average values of PAWC were 371 and 394 mm for soil depths of 1.3 and 1.5 m, respectively. PAWC values were used to design and maintain irrigation treatments during wheat growth. 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. Irrigation within the replicate plots of these treatments were scheduled on the basis of soil water depletion measured with a neutron probe in each plot (details given later) and rainfall. Daily variation of temperature, rainfall and relative humidity at the experimental site (from an automatic weather station adjacent to the experimental site) during wheat growth is shown in Fig. 1.

2.3. Crop Management

Wheat was planted at the experimental site on 6th June 2008. All plots received 100 kg N ha^{-1} of urea and 230 kg ha^{-1} of mono-ammonium phosphate at the time of planting. For weed control, Starane 200 was initially applied at 0.5 l ha^{-1} on 1st July 2008 with a subsequent application of 1 l ha^{-1} on 22nd July 2008. At 63 days after planting (DAP), when the first node of wheat appeared, an additional amount of N-fertilizer (100 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 12 mm to 51 mm), there was little scope for runoff or drainage. Irrigation treatments in various plots were imposed on 64 DAP and continued up to 130 DAP based on soil moisture gains due to irrigation and rainfall and losses due to evapotranspiration (soil water depletion). All replicate plots of T50 received irrigation on 64, 75,104, 111, 117 and 119 DAP and those of T60 on 64, 75, 111, 119, 124 and 129 DAP. Similarly, the plots of T70 received irrigation on 65, 76, 111 and 130 DAP and those of T85 on 65, 74 and 112 DAP. Total water applied during the cropping season for each plot of T50, T60, T70 and T85 irrigation treatments were 203, 152, 79 and 73 mm, respectively. Finally, wheat was harvested on 11th November 2008.

2.4. Soil water content

A neutron probe access tube was installed in each replicate plot to measure the distribution of soil water with depth and time that represented the whole plot throughout the wheat season. A neutron probe (503DR Hydroprobe, Campbell Pacific Nuclear Inc., USA) was used to measure soil water content from the surface to a depth of 1.33 m at 0.1 m depth increments. Standard reference count for the neutron probe was taken in a drum of water prior to field measurements. Neutron count ratio (N) was estimated by dividing each neutron count for a specific soil depth with the standard reference count taken in water. To calibrate the neutron probe, a soil core was taken from each irrigation treatment (T50-T85) at the time when there was large difference (~10%) in water content among the treatments. The cores were divided into 10 cm sections and the moisture content and bulk density of each core was determined gravimetrically. This information was used to develop a relationship between measured count ratios and volumetric soil content (θ, m^3 m^{-3}). Neutron count ratio was converted to the volumetric soil water content (θ, m^3 m^{-3}) with the calibration equation:

$$\theta = 1.36\,N - 0.44. \qquad (R^2 = 0.86,\ n=10,\ P\leq 0.001) \qquad (1)$$

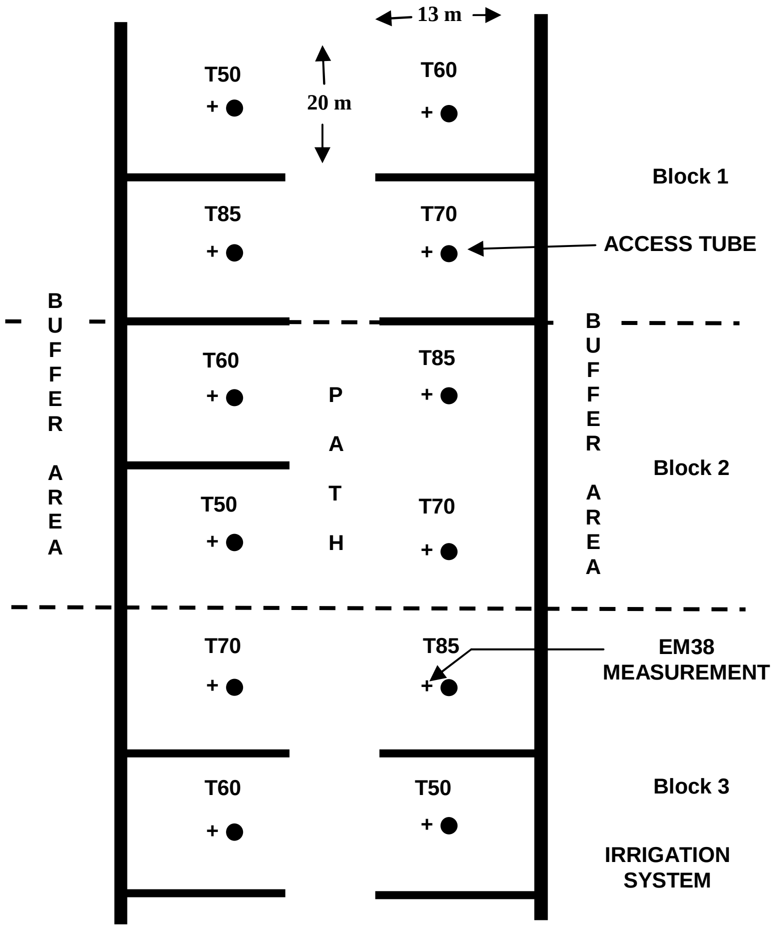

Figure 1. A schematic diagram of the experimental site showing positions of three blocks (or replicates) of four irrigation treatments (T50, T60, T70 and T85) and location of neutron access tubes and EM38 measurements.

2.5. EM38 measurements

The EM38 instrument (Geonics Limited, Ontario, Canada) used in this experiment was based on a spacing of 1 m between a transmitting coil located at one end of the instrument and a receiver coil at the other end, and operated at a frequency of 14.6 kHz. EM38 displayed EC_a in millisiemens per metre (mS m^{-1}) and it could be operated in one of the two measurement modes. In the vertical dipole mode (VM), the measured values of EC_a were essentially a function of the soil properties within 1.5 m depth. In the horizontal dipole mode (HM), EC_a corresponded with soil properties within 0.75 m depth (McNeill, 1980b). EM38 measurements at the soil surface were taken in both VM and HM at the centre of each experimental plot (i.e. at 3 m from the neutron access tubes) on 12 occasions (i.e. 13, 19, 28, 35, 56, 63, 70, 80, 105, 112, 131 and 145 DAP) during the wheat season.

On each measurement occasion, EM38 was first calibrated and nulled according to the manufacturer's instruction before starting a measurement. The position of each EM38 measurement was recorded at the time of first measurement with a hand-held GPS (Global Positioning System) instrument (Model

72, Garmin, Kansas, USA). For subsequent measurements, wooden pegs were driven into the ground at those measurement locations to minimise positional errors. Since the GPS recorded the location in latitude and longitude format (i.e. degree, minute and second), the recorded data were converted to easting and northing by using a UTM conversion excel spread sheet (Dutch, 2007).

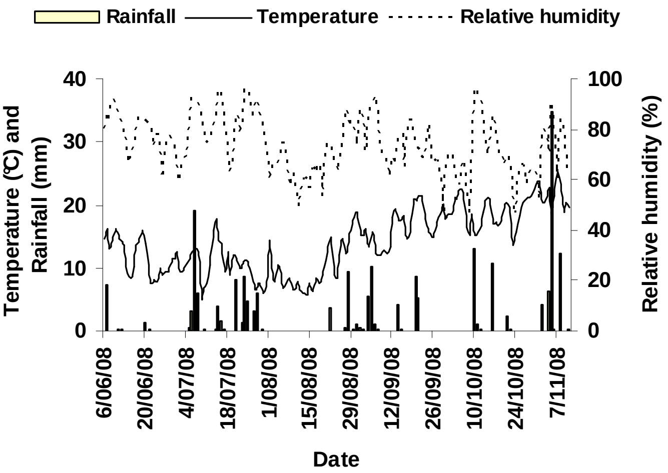

Figure 2. Daily variation of weather parameters during the wheat season.

To gain further insight into the response of EM38 to variation in soil water content at various depths, additional measurements with the EM38 were taken in both VM and HM at 0.1 and 0.4 m height above the ground at the same locations as for previous measurements, but limited to only 7 occasions (i.e. 63, 70, 80, 105, 112, 131 and 145 DAP) during the wheat season. A wooden frame (free of metallic objects, e.g. nails) with an adjustable platform was used to place EM38 probe at the desired heights above the soil surface.

Raising the EM38 above the ground is equivalent to lowering of the EM38 depth-response function, i.e. in VM, an EM38 reading at 0.1 or 0.4 m above the ground is expected to represent EC_a within 1.4 and 1.1 m of soil depth, respectively. With the HM mode, placing EM38 at 0.1 and 0.4 m height above the ground, the effective soil depth of measurement could be reduced to soil depths of 0.65 and 0.35 m, respectively.

2.6. Temperature measurements

As EC_a is influenced by the ambient temperature (Sudduth et al., 2001), air temperature was recorded with an RTD (Resistance Temperature Detector) probe (Omega Corporations, USA) at the time of EM38 measurements. Soil temperature was also measured with the same RTD probe at 5, 10 and 25 cm depths by pushing the probe tip to the appropriate soil depth. Soil temperature was not measured beyond 25 cm depth as variation in soil temperature over time is usually small below 30 cm depth (Jury et al., 1991). Measurement of soil temperature at shallow depths (i.e. 5 and 10 cm) was time consuming because the temperature probe required a longer time (2 to 3 min) to stabilise. When the field was dry, it was difficult to push RTD probe beyond 10 cm depth. So, a stainless steel rod with a conical tip was used to make a pilot hole, few mm less than the desired depth. The temperature probe was then inserted to the desired depth. Both soil temperature at various depths (i.e. 5, 10 and 25 cm depths) and air temperature was measured on 10 occasions (i.e. 13, 19, 28, 35, 56, 63, 70, 105, 131 and 145 DAP) during the wheat season.

2.7. Estimations

The neutron probe (mentioned previously) was used to measure soil water content from the surface to a depth of 1.33 m at 0.1 m depth increments on the same day as all EM38 measurements. The volumetric moisture content was converted to mm of water for each depth and then accumulated to a depth close to the effective depth of sensing of EM38 probe. Estimates of accumulated soil water content (in mm) for five soil depths (i.e. 0.33, 0.63, 0.73, 1.13, and 1.33 m) were used to relate EC_a (mS m^{-1}) measured with EM38 in various modes and heights above the ground. Since soil water content was measured to a maximum depth of 1.33 m, EM38-measured values of EC_a were correlated with this water content in VM at the ground level as well as at 0.1 m height above the ground.

3. Results and discussion

Electrical conductivity of most soils is negligible unless they are moist and contain some soluble salts. Electrical conductivity of any material (including soil) also varies with temperature. Although sensitivity of EM38 can be derived theoretically on the basis of electrical conductivity response of soils to variation in water content and temperature and electrical configuration of EM38, its practical application is limited. EM38 may respond to simultaneous variation in soil water content and temperature in a complex manner. For simplicity, the characteristic response of EM38 to single variables (e.g. water content or temperature) is considered first before considering these variables together.

3.1. Simultaneous variation of soil water content and EC_a

Soil water within 0.73 and 1.33 m depth varied over time as affected by rainfall at the experimental site (Fig. 2) and irrigation treatments, but there was no significant effect of irrigation treatments (T50…T85) on soil water until 70 DAP (Tables 1 and 2), a week after the 1st irrigation was given to specific plots. Spatial variation in soil water content occurred over the field due to imposition of the irrigation treatments with significantly higher soil water content in T50 plots which received the most frequent irrigation (6 irrigations) as compared with the plots of other irrigation treatments. T85 plots consistently remained dry throughout the experiment as these received little irrigation (3 irrigations). Rainfall over the experimental site mainly delayed irrigation in some treatments. Despite erratic distribution of rainfall over the season, it was possible to maintain some differences in soil water content between irrigation treatments.

Mean values of EC_a obtained with VM and HM of EM38 followed a very similar temporal and spatial trend to soil water content (Tables 1 and 2). Of all 12 measurement occasions, significant spatial variation in EC_a due to irrigation treatments occurred only after the irrigation treatments were imposed on 64 DAP. Plots which were irrigated most frequently (T50 plots) indicated significantly higher EC_a than the plots which were irrigated least frequently (T85 plots). The least significant difference (LSD) values shown in Tables 1 and 2 indicate that the magnitude of spatial and temporal variation with EC_a was generally smaller than the variation with soil water over the experimental site. Similarities in the variation of EC_a and soil water over the experimental site indicates that EM38 has a good potential for mapping spatial and temporal variation in water content in soils of high clay content (with high CEC) as these soils are capable of exhibiting a wide range of EC_a (Brevik et al., 2006).

Assuming contribution from other soil properties (e.g. soil temperature) towards variation of EC_a within the experimental site was small, data in Fig. 3 suggested considerable dependency of EC_a on soil water content within 1.33 m depth. The relationship between EC_a and soil water was largely linear in the VM measurement mode of EM38 when soil water <550 mm (Fig. 3a). However, a departure from linearity occurred (shown by the curve in Fig. 3a) when soil within 1.33 m depth was too wet (soil water >550 mm). The relationship between EC_a and soil water could be best represented as

$$y = 211.76\,[1 - 16.01\,e^{-0.007x}] \qquad (n = 144,\ R^2 = 0.77,\ P \le 0.001), \qquad (2)$$

where $y = EC_a$ (mS m^{-1}) measured in VM of EM38 and x = soil water (mm) within 1.33 m depth of soil.

Similar measurements of EC_a with EM38 in HM also showed a linear increase in EC_a with increase in soil water within 0.73 m depth (Fig. 3b). Despite the range of EC_a and soil water values in Fig. 3b were considerably less than Fig. 3a (as the soil depth was reduced by 0.6 m), the departure from linearity was still evident at high water content requiring a nonlinear equation of the type,

$$y = 202.46\,[1 - 3.369\,e^{-0.007x}]. \qquad (n = 144,\ R^2 = 0.76,\ P \le 0.001), \qquad (3)$$

where y = EC_a (mS m^{-1}) measured in HM of EM38 and x = soil water (mm) within 0.73 m depth. Nonlinear behaviour of EM38 to soil water in HM indicates that the vast majority of the response of EM38 was from the top portion of the explored soil depth (McNeill, 1992).

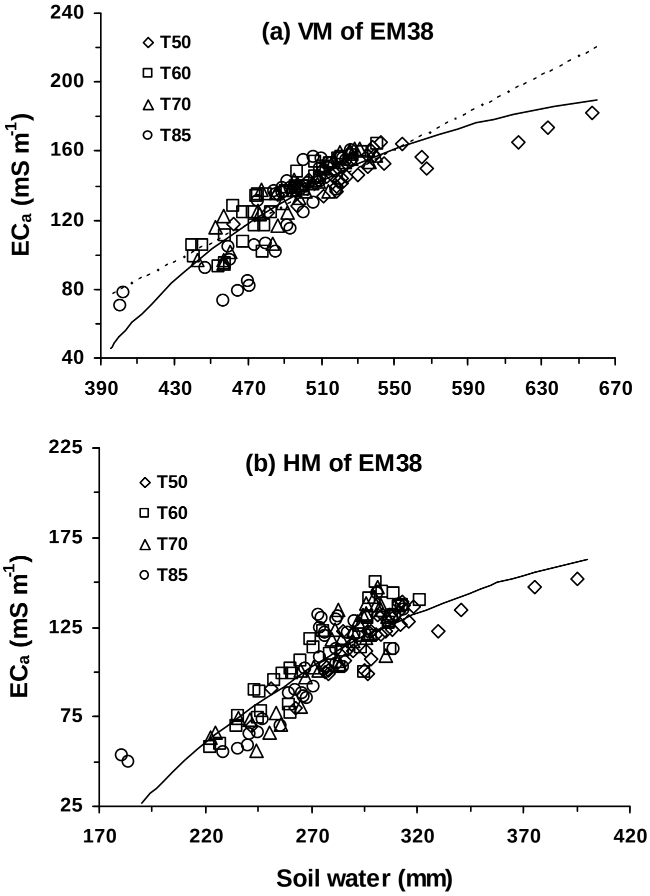

Figure 3. The relationship between EC_a measured (a) in the vertical mode (VM) of EM38 with water content within the top 1.33 m of soil and (b) in the horizontal mode (HM) with water content within the top 0.73 m of soil as measured for various irrigation treatments.

3.2. Effects of placing EM38 at various heights

The effect of irrigation treatments on values of EC_a measured with EM38 in VM at 0.1 and 0.4 m above ground and soil water within related depths are shown in Table 3. When EM38 is placed in VM on the ground, its sensing zone is assumed to extend to a soil depth of 1.5 m. Thus, when EM38 is placed at 0.1 m or 0.4 m height above the ground, the sensing depth should correspond with soil depths of 1.4 m and 1.1 m, respectively. However, our measurement of soil water was limited to 1.33 m depth. Therefore, we compared EC_a readings at 0.1 m height above ground with maximum depth of soil water (i.e. 1.33 m) in Table 1. When EM38 was placed at 0.4 m height above ground, we used soil water within 1.13 m in stead of 1.1 m depth (Table 3). It can be seen from Tables 1 and 3 that significant effect of irrigation treatments was observed for soil water on 4-5 occasions from 80 DAP onward. In contrast, irrigation treatments affected EC_a to a lesser extent (on 3-4 occasions) than soil water (Table 3). In clay soils, redistribution of water following irrigation usually takes longer than in coarse textured soils. This may delay the effects of irrigation treatments to be observed in the field as seen from the data in Tables 1 and 3. Irrigation was given on 64 DAP, but significant effects of irrigation treatments on soil water was not observed until 80 DAP. As EC_a is a measure of soluble salts in soil, data in Table 3 show that EM38 was able to detect the differences between irrigation treatments for shallow depths (in VM at 0.4 m height above ground) earlier than soil water measured with the neutron probe. However, EM38 was not able to detect small differences in water content among irrigation treatments (LSD ~ 13-14 for soil water) as the treatment effects on EC_a were not significant with VM of EM38 at 0.1 and 0.4 m above the ground at 105 and 112 DAP, respectively (Table 3). On most occasions, EM38 was sensitive enough to differentiate the wettest part of the field (T50 plots) from the driest, least frequently irrigated plots (T85 plots) with significantly higher EC_a.

Table 1. Effects of irrigation treatments (T50…T85) on soil water within 1.33 m depth and corresponding value of EC_a with VM of EM38 for the wheat field on selected measurement dates (indicated as days after planting, DAP). Mean values with a different superscript letter are significantly different (P≤0.05) when compared with the least significant difference (LSD). NS indicates no significant effects of irrigation treatments during the analysis of variance.

DAP	Soil water (mm) within 1.33 m depth				LSD (mm)
	T50	T60	T70	T85	
13	522.2	494.3	500.4	496.9	NS
19	529.1	509.0	517.7	509.2	NS
28	531.9	510.3	514.9	507.3	NS
35	530.4	507.5	516.0	505.7	NS
56	517.9	498.1	508.3	495.3	NS
63	513.0	494.1	506.5	494.1	NS
70	505.6	488.1	496.3	486.3	NS
80	614.7[a]	518.9[b]	520.7[b]	508.4[b]	60.9
105	523.4[a]	472.7[c]	491.7[b]	482.5[bc]	15.4
112	503.4[a]	463.7[b]	478.2[b]	470.6[b]	17.8
131	567.9[a]	466.2[b]	464.4[b]	445.6[b]	54.2
145	508.7[a]	442.2[b]	453.3[b]	439.0[b]	52.3
	EC_a (mS m^{-1}) in VM				LSD (mS m^{-1})
13	153	142	145	141	NS
19	149	147	154	149	NS
28	157	147	149	147	NS
35	157	149	151	151	NS
56	150	140	146	145	NS
63	141	143	144	128	NS
70	143	131	136	120	NS
80	173[a]	156[b]	153[b]	141[b]	21
105	142[a]	118[bc]	131[ab]	108[c]	15
112	132[a]	107[bc]	121[ab]	96[c]	17
131	155[a]	108[b]	106[bc]	81[c]	26
145	132[a]	103[b]	98[b]	82[b]	26

Using EM38 in HM at 0.1 m height above the ground, values of soil water (within 0.63 m depth) and EC_a were equally sensitive to irrigation treatments (Table 4). Placing EM38 at 0.4 m height above ground in HM, EC_a values reflected the effect of irrigation treatments better than soil water measured with the neutron probe as significant effect of irrigation treatments was observed on 2 occasions for soil water measured with neutron probe, but on 5 occasions for EC_a measured with EM38. Thus, EM38 can be considered to be quite sensitive to changes in soil water at shallow depths due to irrigation.

When EM38 is placed at some height above the ground, the characteristic response of EM38 (e.g. linear or nonlinear) to soil water and temperature is not known. Therefore, it is important to examine the characteristic response of EM38 to single variables, e.g. soil water. The response of EM38 to soil water content (within 1.33 and 1.13 m depth) due to placement of EM38 at 0.1 and 0.4 m above the ground ($VM_{0.1}$ and $VM_{0.4}$, respectively) was tested by plotting values of EC_a against soil water (Fig. 4). During these evaluations the range of soil water was similar to those in Fig. 3, but the range of EC_a values was different. A linear increase in EC_a with increased in soil water content in these figures suggest that EC_a measured in $VM_{0.1}$ or $VM_{0.4}$ represented soil water for these soil depths better than the nonlinear dependence found when it is placed on the ground (Fig. 3). The relationship between EC_a and soil water for $VM_{0.1}$ could be best represented as

$$y = 0.45\,x - 108.67 \qquad (n = 84,\ R^2 = 0.70,\ P \leq 0.001), \qquad (4)$$

and for $VM_{0.4}$, it was

$$y = 0.42\,x - 81.77 \qquad (n = 84,\ R^2 = 0.71,\ P \leq 0.001). \qquad (5)$$

For both equations, $y = EC_a$ (mS m^{-1}) measured in $VM_{0.1}$ or $VM_{0.4}$ of EM38 and x = soil water (mm) within 1.33 and 1.13 m depth of soil, respectively. For calibration of any equipment (e.g. neutron probe or EM38) a linear than a nonlinear relationship between variables is preferred as the slope of a linear relationship is constant whereas for a nonlinear relationship, the slope becomes a function of the dependent variable. These results collectively indicate that by placing the EM38 at various heights above the ground in VM, it is possible to predict water content within 1-1.5 m depth with reasonable confidence.

Table 2. Effects of irrigation treatments (T50…T85) on soil water within 0.73 m depth and corresponding value of EC_a with HM of EM38 for the wheat field on selected measurement dates (indicated as days after planting, DAP). Mean values with a different superscript letter are significantly different (P≤0.05) when compared with the least significant difference (LSD). NS indicates no significant effects of irrigation treatments during the analysis of variance.

DAP	Soil water (mm) within 0.73 m depth				LSD (mm)
	T50	T60	T70	T85	
13	305.4	288.7	290.9	286.9	NS
19	308.3	304.0	300.3	292.7	NS
28	309.9	295.0	297.5	289.4	NS
35	309.2	297.4	299.7	291.4	NS
56	301.9	288.8	293.6	283.3	NS
63	294.3	283.1	289.1	277.1	NS
70	287.2	275.0	279.6	268.8	NS
80	361.2^a	302.7^b	293.5^b	282.9^b	50.1
105	280.5^a	254.5^b	267.6^b	258.0^b	14.3
112	268.4^a	244.4^b	256.3^b	248.0^b	12.3
131	322.4^a	250.7^b	241.1^b	224.2^b	39.7
145	266.7	228.1	233.7	220.4	NS
	EC_a (mS m^{-1}) in HM				LSD (mS m^{-1})
13	124	133	133	118	NS
19	130	134	132	129	NS
28	130	133	132	121	NS
35	136	127	132	125	NS
56	122	124	134	135	NS
63	111	104	114	105	NS
70	116	105	110	98	NS
80	145^a	121^b	116^b	107^b	17
105	102^a	91^{ab}	100^a	77^b	17
112	98^a	81^b	75^b	71^b	12
131	119^a	81^b	63^b	63^b	16
145	84^a	63^b	71^{ab}	59^b	16

Table 3. Effects of irrigation treatments on soil water within 1.13 m depth and EC_a measured with the vertical mode of EM38 after it was placed at 0.1 and 0.4 m height above ground ($VM_{0.1}$ and $VM_{0.4}$, respectively) in the wheat field on selected measurement dates (indicated as days after planting, DAP). Mean values with a different superscript letter(s) are significantly different (P≤0.05) when compared with the least significant difference (LSD). NS indicates no significant effects of irrigation treatments during the analysis of variance.

DAP	Soil water (mm) within 1.13 m depth				LSD (mm)
	T50	T60	T70	T85	
63	435.5	417.4	431.3	416.2	NS
70	428.3	411.2	421.5	408.5	NS
80	531.2[a]	442.0[b]	442.7[b]	428.7[b]	62.9
105	440.9[a]	393.9[c]	413.9[b]	402.8[bc]	13.6
112	422.5[a]	384.7[c]	401.0[b]	390.8[bc]	14.0
131	484.1[a]	389.6[b]	387.5[b]	367.7[b]	49.7
145	417.9	365.3	376.9	362.3	NS
	EC_a (mS m^{-1}) with $VM_{0.1}$				LSD (mS m^{-1})
	T50	T60	T70	T85	
63	129	124	134	118	NS
70	130	125	127	113	NS
80	164[a]	141[bc]	146[ab]	124[c]	18
105	128	111	124	97	NS
112	119[a]	95[b]	108[ab]	95[b]	15
131	136[a]	91[b]	95[b]	80[b]	19
145	109	93	87	79	NS
	EC_a (mS m^{-1}) with $VM_{0.4}$				
63	110	101	110	103	NS
70	109[a]	101[ab]	111[a]	96[b]	11
80	135[a]	112[bc]	123[ab]	100[c]	16
105	100[a]	85[ab]	100[a]	77[b]	15
112	93	78	82	76	NS
131	110[a]	66[b]	70[b]	64[b]	20
145	87	72	73	66	NS

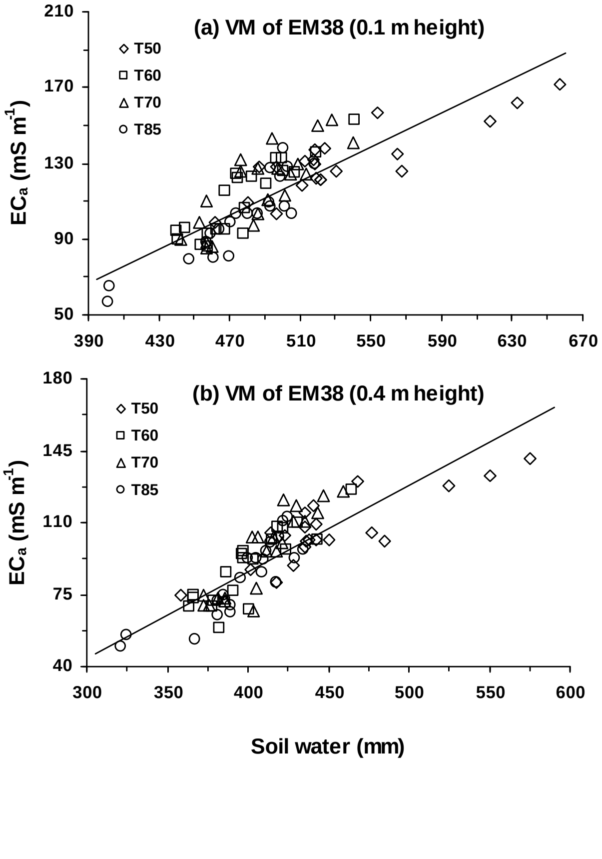

Figure 4. The relationship between EC_a measured in vertical mode (VM) of EM38 at (a) 0.1 m and (b) at 0.4 m height above the ground with water content within the top 1.33 and 1.13 m of soil, respectively for various irrigation treatments.

Table 4. Effects of irrigation treatments on soil water within 0.63 and 0.33 m depth and EC_a measured with the horizontal mode of EM38 after it was placed at 0.1 and 0.4 m height above ground ($HM_{0.1}$ and $HM_{0.4}$, respectively) in the wheat field on selected measurement dates (indicated as days after planting, DAP). Mean values with a different superscript letter are significantly different (P≤0.05) when compared with the least significant difference (LSD). NS indicates no significant effects of irrigation treatments during the analysis of variance.

DAP	Soil water (mm) within 0.63 m depth				LSD (mm)
	T50	T60	T70	T85	
63	258.9	249.9	253.7	242.7	NS
70	252.0	241.9	244.1	233.7	NS
80	314.3^{a}	267.8^{b}	256.5^{b}	247.1^{b}	44.3
105	240.3^{a}	220.8^{b}	231.0^{ab}	222.8^{b}	13.0
112	231.5^{a}	211.6^{b}	221.7^{ab}	213.5^{b}	12.8
131	278.9^{a}	216.0^{b}	204.4^{b}	188.1^{b}	37.3
145	225.9	194.8	197.4	185.1	NS
	Soil water (mm) within 0.33 m depth				
63	140.7	139.0	140.8	130.5	NS
70	134.6	132.0	131.8	124.2	NS
80	164.7^{a}	151.9^{ab}	140.3^{b}	133.3^{b}	22.3
105	116.6	112.0	118.9	108.8	NS
112	113.7	105.7	111.0	103.2	NS
131	134.3^{a}	106.4^{ab}	91.7^{bc}	75.9^{c}	28.5
145	99.5	87.3	89.1	75.3	NS
	EC_a (mS m^{-1}) with $HM_{0.1}$				LSD (mS m^{-1})
	T50	T60	T70	T85	
63	103	98	105	96	NS
70	103	96	106	88	NS
80	125^{a}	107^{bc}	110^{b}	96^{c}	13
105	93^{a}	80^{b}	89^{a}	62^{c}	7
112	90^{a}	72^{b}	75^{b}	66^{b}	12
131	96^{a}	68^{b}	61^{b}	56^{b}	16
145	68	60	63	52	NS
	EC_a (mS m^{-1}) with $HM_{0.4}$				
63	79	71	82	73	NS
70	77	73	73	65	NS
80	102^{a}	80^{b}	84^{b}	73^{b}	12
105	67^{ab}	56^{bc}	77^{a}	49^{c}	11
112	64^{a}	50^{bc}	52^{b}	43^{c}	8
131	62^{a}	40^{b}	44^{b}	38^{b}	6
145	41^{a}	33^{ab}	40^{a}	28^{b}	8

By placing EM38 at 0.1 and 0.4 m height above the ground in the HM ($HM_{0.1}$ and $HM_{0.4}$, respectively), EC_a also increased with increase in soil water content within 0.63 and 0.33 m soil depths, respectively (Fig. 5). Although variation in EC_a with soil water was not uniform in HM (due to slight nonlinearity observed with $HM_{0.4}$ at low soil water content), these results suggest that it is possible to predict soil water content at much shallower depths (i.e. 0.3-0.6 m) by selecting appropriate heights above the ground in HM of EM38. The relationship between EC_a and soil water for $HM_{0.1}$ and $HM_{0.4}$ could be best represented as

$$y = 0.59\,x - 53.47 \qquad (n = 84,\ R^2 = 0.78,\ P \leq 0.001) \qquad (6)$$

and

$y = 12.916\ e^{0.013\,x}$ $(n = 84,\ R^2 = 0.81,\ P \leq 0.001)$, (7)

respectively. For both equations, y = EC_a (mS m^{-1}) measured in $HM_{0.1}$ or $HM_{0.4}$ of EM38 and x = soil water (mm) within 0.63 and 0.33 m depth of soil, respectively.

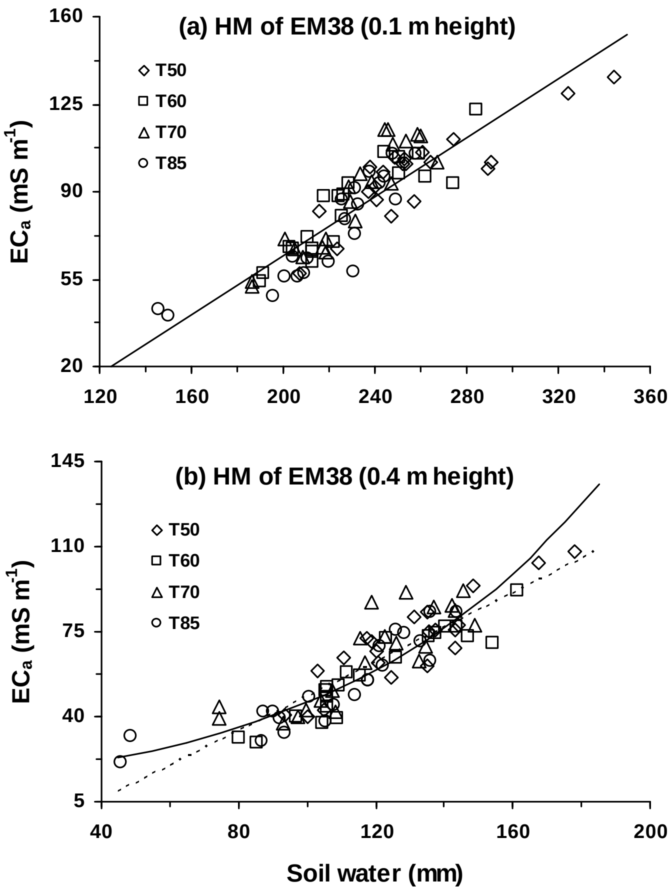

Figure 5. The relationship between EC_a measured in horizontal mode (HM) of EM38 at (a) 0.1 m and (b) at 0.4 m height above the ground with water content within the top 0.63 and 0.33 m of soil, respectively for various irrigation treatments.

When EM38 is placed at a certain height above the ground, values of EC_a are usually reduced to a greater extent in HM than VM for EM38 that allows sensing of soil properties at shallow depths (Sudduth et al., 2001; Abdu et al., 2007). Improvements in the statistics of regression models for HM (in Eqns. 6 and 7) over VM (Eqns. 4 and 5) could be due to the greater contribution of shallow soil layers to EC_a than the deeper soil layers (McNeill, 1992). High accuracy of EM38 in HM observed in this study also suggests that it is possible to measure temporal changes in water content of surface soils where rapid changes in soil water are likely to occur due to rainfall or irrigation and evapotranspiration.

3.3. Effect of temperature on EC_a

Soil temperature is an important factor that affects electrical conductivity (EC) of soil. Although EM38 does not require direct contact with the soil, diurnal and seasonal variation of air/soil temperature is expected to affect EC_a (Huth and Poulton, 2007). There are two sources of variability in EC_a due to a change in temperature: (1) temperature-dependent change in soil and (2) instrumental drift caused by the temperature effects on the processing circuitry of EM38 (Abdu et al., 2007). When EM38 is used over a long period (e.g. several hours) on a given day, EM38 needs to be calibrated as it is susceptible to drift due to changes in temperature (Sudduth et al., 2001). In our study, instrumental drift was largely avoided as there were only 12 measurement locations within a small experimental field that took <30 min to complete. However, seasonal variation in air temperature during the wheat season (Fig. 2) could not be controlled over the span of all measurements. Seasonal variation in air temperature and soil temperature at 5, 10 and 25 cm depths for various irrigation treatments (Table 5) indicated that the range of seasonal variation in air temperature was consistently greater than the soil temperature at any depth for all irrigation treatments. The range of soil temperature observed for various irrigation treatments was similar and declined with depth (Table 5).

Table 5. Range of air and soil temperature (at 5, 10 and 25 cm depths) for T50, T60, T70 and T85 irrigation treatments during the wheat season.

Irrigation treatments	Range of air temperature (°C)	Range of soil temperature (°C) at		
		5 cm depth	10 cm depth	25 cm depth
T50	14.2-32.9	10.1-25.7	10.6-23.3	11.4-22.1
T60	15.1-32.9	10.3-25.9	10.8-23.1	12.2-22.5
T70	14.8-33.9	10.4-28.9	10.7-25.6	12.5-23.2
T85	14.9-34.0	10.4-29.3	10.8-26.6	12.1-23.9

Plots of raw values of EC_a (i.e. without correction for temperature) against average soil temperature (over 5, 10 and 25 cm depths) showed a small initial increase in EC_a with increase in soil temperature, but mostly EC_a declined after reaching a maximum value for both VM and HM of EM38 (Fig. 6). Quadratic regression equations were found to be most appropriate to describe the variation of EC_a with seasonal variation in air temperature and soil temperature at various depths (Table 6). As the peak value (the maxima) of a differentiable function can be estimated by setting the first derivative of that function (shown in Table 6 as regression equations) to zero, the peak values of EC_a determined for VM and HM of EM38 in Fig. 6 were 15.7 and 15.8 °C, respectively. Although the response of EM38 to diurnal variation in temperature has been examined (Brevik et al., 2004), very little data exists in the literature on seasonal variation of EC_a with temperature.

Table 6. Regression equations and coefficient of determination (R^2) for the relationship between EC_a (y, mS m^{-1}) in VM and HM of EM38 and temperature (both soil and air, x, °C) for the wheat field. No. of data pairs (n) used for each regression was 120 and $P \leq 0.001$.

Temperature	Regression equation	R^2
	VM of EM38	
Air	$y = -0.240\,x^2 + 9.705\,x + 49.274$	0.418
Soil (5 cm depth)	$y = -0.356\,x^2 + 11.517\,x + 56.951$	0.506
Soil (10 cm depth)	$y = -0.483\,x^2 + 14.292\,x + 43.875$	0.550
Soil (25 cm depth)	$y = -0.873\,x^2 + 26.838\,x - 57.401$	0.558
Soil (average)	$y = -0.585\,x^2 + 18.358\,x + 6.5042$	0.568
	HM of EM38	
Air	$y = -0.366\,x^2 + 15.490\,x - 37.419$	0.544
Soil (5 cm depth)	$y = -0.493\,x^2 + 16.297\,x - 4.957$	0.624
Soil (10 cm depth)	$y = -0.601\,x^2 + 17.801\,x - 3.812$	0.638
Soil (25 cm depth)	$y = -1.065\,x^2 + 32.593\,x - 122.54$	0.654
Soil (average)	$y = -0.765\,x^2 + 24.244\,x - 61.956$	0.683

As EC is usually expressed at a standard temperature of 25 °C, a correction factor is often used to extrapolate EC_a measured at a temperature other than 25 °C to EC_a at 25 °C. Huth and Poulton (2007) used a complex EC_a-temperature correction scheme by adapting the scheme commonly used for EC-temperature correction (Richards, 1954). A similar approach was also used by Reedy and Scanlon (2003) that indicated the correction factor to vary within 0.9 for warm season to 1.47 for cool season within the temperature range of 3-35 °C. In our study, it was not obvious that a temperature correction scheme would improve estimation of water content from EM38 measurements because the variation of EC_a with temperature occurred over all the irrigation treatments (Fig. 6). Regression of temperature-corrected EC_a against soil water was poor when compared with the data shown in Fig. 3. Considerable improvement in EC_a-water content relationship could be gained by including temperature as an additional variable in multiple regression equations as shown below.

$$EC_a(V) = -1436.14 + 254.91 \ln\theta_V - 0.037\, T^2 \quad (n = 120,\ R^2 = 0.82,\ P\leq0.001); \quad (8)$$

$$EC_a(H) = -348.67 + 97.82 \ln\theta_H - 0.006\, T^2 \quad (n = 120,\ R^2 = 0.98,\ P\leq0.001). \quad (9)$$

In these equations, $EC_a(V)$ and $EC_a(H)$ are EC_a (mS m^{-1}) values measured in vertical and horizontal modes of EM38, respectively; θ_V and θ_H respectively refer to soil water (mm) within 1.33 and 0.73 m soil depths and T, the average soil temperature (°C) within 5-25 cm depth.

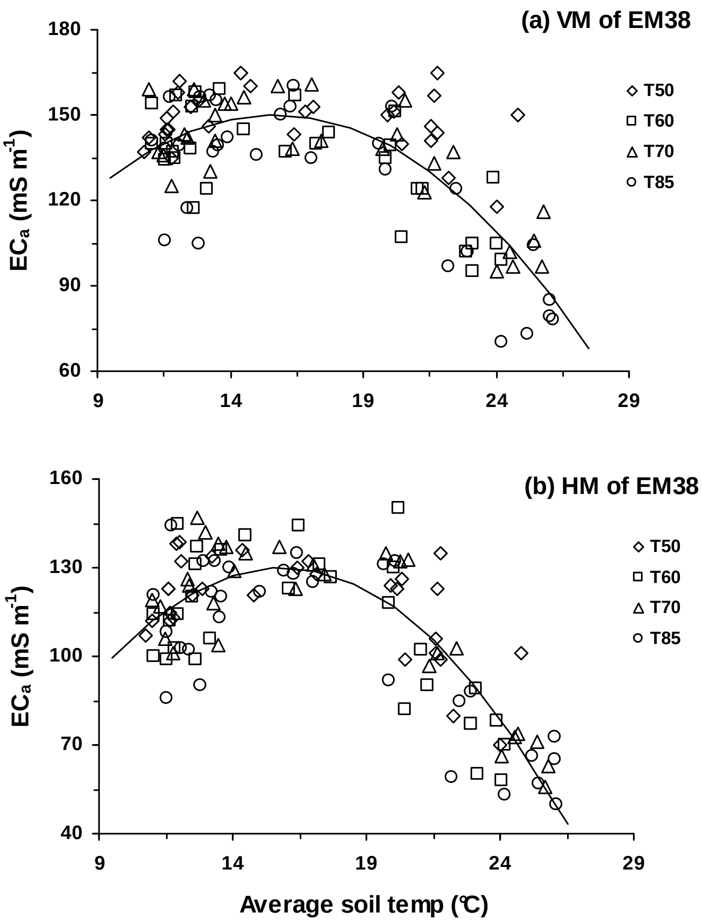

Figure 6. The relationship between EC_a measured in (a) vertical mode (VM) of EM38 and (b) horizontal mode (HM) with average soil temperature within 5 - 25 cm depth for various irrigation treatments.

3.4. Spatial distribution of soil water and EC_a

As EM38 and water content measurements were made at fixed positions (with known GPS record) and there was a strong dependency of EC_a on soil water content (Figs. 3-5), it is useful to compare EC_a maps with soil water maps on a given day of measurement to gain additional confidence on the usefulness of EM38 to predict spatial distribution of soil water content. Fig. 7 shows a typical spatial variation in EC_a measured in VM and corresponding variation in soil water for all 12 plots of the experimental field. Filled circles on these maps represent the measurement location for each plot for soil water and EC_a with labels denoting irrigation treatments (T50…T85) and replicates (R1…R3). Fig. 7 was generated with the software Surfer that used weighted average interpolation algorithm during kriging and spline smoothing.

Areas within these maps with a darker shade of blue indicate a relatively high value of EC_a that coincides with a similar location in the field of high soil water content within the depth-response range of EM38 (Fig. 7). In a similar way, areas of lighter shade of blue (almost white) depict low values for both EC_a and soil water content. Since areas of the field with T50 and T85 treatments denote areas of lowest and highest soil water deficit respectively, frequent mapping of EC_a can be used to assess soil water within crop fields. Such assessment would permit delineation of zones of available water to apply spatially variable quantities of water to reduce soil water deficit and achieve higher water use efficiency (Hedley and Yule, 2009) through the practice of precision irrigation. It may be possible to schedule irrigation in an entire field (of uniform clay soil) when the EC_a reaches a critical value. Greater confidence with irrigation scheduling with EM38 assessment is possible when both EC_a and soil temperature are measured and adequate consideration of Equations 8 and 9 is made.

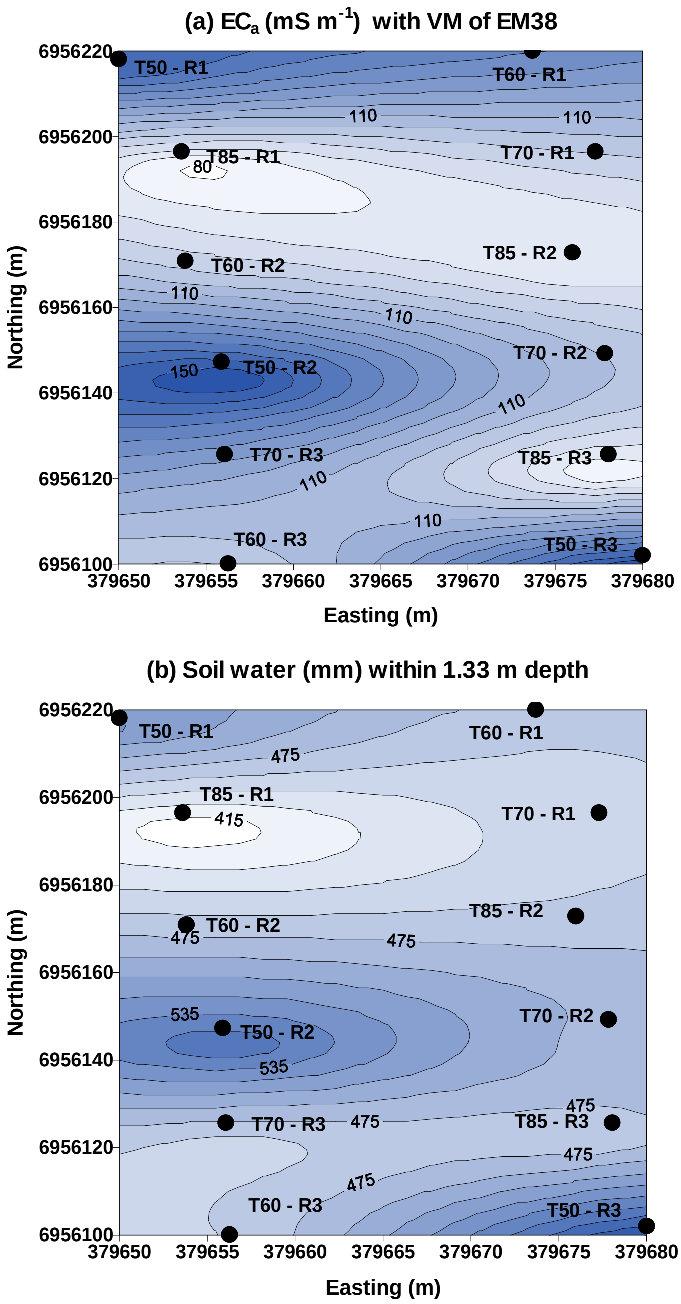

Figure 7. Spatial variation in (a) EC_a measured with VM of EM38 and (b) soil water content within 1.33 m at the irrigation experiment site at 131 days after planting wheat. Filled circles indicate the position of EM38 measurements for each plot. R1, R2 and R3 are replicates of irrigation treatments

T50, T60, T70 and T85. Contour lines show EC_a (mS m^{-1}) and soil water (mm) in Figs. a and b, respectively.

3.5. Implications to soil water assessment for irrigation

Since EMI techniques used for the measurement of EC_a can provide a large amount of spatial information relatively quickly and economically when compared with direct but invasive measurements of soil water content with neutron probe or other soil water sensors, this technique could be used to apply variable quantities of irrigation within a field. However, EC_a maps should be used to assess soil water distribution when spatial variation in EC_a is largely due to the variation in soil water content.

As spatial distribution of water content in large crop fields is difficult to monitor without employing a large number of sensors distributed over many locations, uniform amount of irrigation is usually applied to the whole field assuming the field to have a homogeneous water content. As a consequence, some part of the field may be receiving excess water while other part receives less water. By conducting EM38 surveys it may be possible to divide the field into different irrigation application zones depending on the value of EC_a. Using EC_a maps, it would be possible to apply the desired quantity of water such that no part of the field receives excess or less water. With this type of water application, the distribution efficiency of irrigation can be improved which reduces the scope of leaching of fertilizers and other chemicals beyond the root zone to the groundwater with an overall reduction in environmental risks associated with crop production. If the spatial variation in EC_a in a field is due to the spatial variation of a soil property that does not contribute towards variation in soil water content, then EC_a maps should not be used to predict soil water in that situation. In those situations, it may be used to distinguish soil types as a result of variation in soil properties in horizontal and vertical directions. It is important to note that EC_a measurements with EM38 may not work for all soils and landscapes; and thus, require an understanding of soils prior to interpreting EC_a results for specific applications.

4. Conclusions

Simultaneous measurements of apparent electrical conductivity (EC_a) with EM38 equipment and soil water with neutron probe indicates that good estimates of soil water content can be made from EC_a data within the root zone of agricultural crops. Although EM38 was partly sensitive to variation in soil and air temperature, it is possible to use that information for soil water estimation using both VM and HM modes of EM38 and by placing EM38 at various heights above the ground. Since EC_a is a complex function of several soil properties, accurate prediction of the absolute quantity of soil water at a given position in a crop field is difficult. However, relative distribution of dry and moist areas can be assessed easily with this technique over a range of soil depths.

Acknowledgements

We wish to extend our thanks to Dr. Jose O. Payero and Mr. Graham Harris from Agri-Science Queensland, Department of Employment, Economic Development and Innovation for access to the experimental site for data collection. This research was supported by the Cooperative Research Centre for Irrigation Futures (CRC IF) and received additional support from Growing the Smart State PhD funding program of the Queensland Government.

References

Abdu, H., Robinson, D.A., Jones, S.B., 2007. Comparing bulk soil electrical conductivity determination using the DUALEM-1S and EM38-DD electromagnetic induction Instruments. Soil Sci. Soc. Am. J. 71, 189-196.

Batte, M.T., 2000. Factors influencing the profitability of precision farming systems. J. Soil Water Conserv. 55, 12–18.

Brevik, E.C., Fenton, T.E., 2002. Influence of soil water content, clay, temperature, and carbonate minerals on electrical conductivity readings taken with an EM-38. Soil Surv. Horiz. 43**,** 9-13.

Brevik, E.C., Fenton, T.E., Horton, R., 2004. Effect of daily soil temperature fluctuations on soil electrical conductivity as measured with the Geonics® EM-38. Precision Agric. 5, 145-152.

Brevik, E.C., Fenton, T.E., Lazari, A., 2006. Soil electrical conductivity as a function of soil water content and implications for soil mapping. Precision Agric. 7, 393-404.

Bullock, D.S., Bullock, D.G., 2000. From agronomic research to farm management guidelines: A primer on the economoics of information and precision technology. Precision Agric. 2**,** 71-101.

Corwin, D.L., Lesch, S.M., 2005. Apparent soil electrical conductivity measurements in agriculture. Comput. Electron. Agric. 46**,** 11-43.

Dutch, S., 2007. Converting UTM to Latitude and Longitude (Or Vice versa). http://www.uwgb.edu/dutchs/UsefulData/UTMFormulas.htm. Viewed on 29.10.2007.

Friedman, S.P., 2005. Soil properties influencing apparent electrical conductivity: A review. Compute Electron. Agric. 46**,** 45-70.

Gardner, E.A., 1985. Identification of soils and interpretation of soil data, Chapter: Soil Water, Australian Society of Soil Science Inc., Qld Branch, Brisbane. pp. 197-234.

Havlin, J., Beaton, J., Tisdale, S., Nelson, W., 1999. Soil Fertility and Fertilizers, Prentice Hall, New Jersey, USA.

Hedley, C.B., Yule, I.Y., Eastwood, C.R., Shepherd, T.G., Arnold, G., 2004. Rapid identification of soil textural and management zones using electromagnetic induction sensing of soils. Aust. J. Soil Res. 42, 389–400.

Hedley, C.B., Yule, I.J., 2009. Soil water status mapping and two variable-rate irrigation scenarios. Precision Agric. 10**,** 342-355.

Heermann, D.F., Hoeting, J., Duke, H.R., Westfall, D.G., Buchleiter, G.W., Westra, P., Peairs, F.B., Fleming, K., 2000. Irrigated precision farming for corn production. Proceedings of Second International Conference on Geospatial Information in Agriculture and Forestry, Lake Buena Vista, Florida, pp. 144-151.

Huth, N.I., Poulton, P.L., 2007. An electromagnetic induction method for monitoring variation in soil moisture in agroforestry systems. Aust. J. Soil Res. 45**,** 63-72.

Isbell, R.F., 1996. The Australian Soil Classification, CSIRO Publishing, Collingwood, Victoria, Australia.

Jury, W.A., Gardner, W.R., Gardner, W.H., 1991. Soil Physics, 5th ed. John Wiley and Sons, Inc., New York, USA.

Kachanoski, R.G., Gregorich, E.G., Van Wesenbeck, I.J., 1988. Estimating spatial variations of soil water content using non contacting electromagnetic inductive methods. Can. J. Soil Sci. 68**,** 715-722.

Kachanoski, R.G., De Jong, E., Van Wesenbeck, I.J., 1990. Field scale patterns of soil water storage from non-contacting measurements of bulk electrical conductivity. Can. J. Soil Sci. 70**,** 537-541.

Khakural, B.R., Robert, P.C., Hugins, D.R., 1998. Use of non-contacting electromagnetic inductive method for estimating soil moisture across a landscape. Commun. Soil Sci. Plant Anal. 29**,** 2055-2065.

Mcbride, R.G., 2003. Relationships between soil properties and yield variability and the potential for establishing management zones for site-specific management in North Carolina. PhD Thesis. North Carolina State University, USA.

McNeill, J.D., 1980a. Electrical conductivity of soil and rocks. Technical Note TN-5, Geonics Ltd., Mississauga, Ontario, Canada.

McNeill, J.D., 1980b. Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6, Geonics Ltd., Mississauga, Ontario, Canada.

McNeill, J.D., 1992. Rapid, accurate mapping of soil salinity by electromagnetic ground conductivity meters, in: Advances in Measurements of Soil Physical Properties: Bringing Theory into Practice, SSSA Special Publication 30, ASA, CSSA, SSSA, Madison, WI, USA, pp. 209–229.

Ratliff, L. F., Ritchie, J. T. & Cassel, D. K. (1983). A survey of field-measured limits of soil water availability and related to laboratory-measured properties. Soil Sci. Soc. Am. J. 47**,** 770-775.

Reedy, R.C., Scanlon, B.R., 2003. Soil water content monitoring using electromagnetic induction. J. Geotech. Geoenviron. Eng. 129**,** 1028-1039.

Rhoades, J.D., 1992. Instrumental field methods of salinity appraisal, in: Advances in Measurements of Soil Physical Properties: Bringing Theory into Practice, SSSA Special Publication 30, ASA, CSSA, SSSA, Madison, WI, USA, pp. 231–248.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J., Alves, W.J., 1989. Soil electrical conductivity and soil salinity: New formulations and calibrations. Soil Sci. Soc. Am. J. 53**,** 433-439.

Richards, L. A. (Ed.), 1954. Diagnostic and improvement of saline and alkali soils. U.S. Dept of Agriculture Handbook No. 60, U.S. Govt. Print. Office, Washington DC, USA.

Ritchie, J. T. (1981). Soil water availability. Plant Soil 58**,** 81-96.

Sanders, J., Jim, H., Kvien, C., Stuart, P., 2000. Analysis of the benefits of precision irrigation in South Georgia, http://nespal.cpes.peachnet.edu/agwateruse/initiative/pivot analysis.pdf, Viewed on 10.7.2006.

Sudduth, K.A., Drummond, S.T., Kitchen, N.R., 2001. Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. Comput. Electron. Agric. 31**,** 239-264.

Sudduth, K.A., Kitchen, N.R., Wiebold, W.J., Batchelor, W.D., Bollero, G.A., Bullock, D.G., Clay, D.E., Palm, H.L., Pierce, F.J., Schuler, R.T., Thelen, K.D., 2005. Relating apparent electrical conductivity to soil properties across the north-central USA. Comput. Electron. Agric. 46, 263-283.

Triantafilis, J., Lesch, S.M., 2005. Mapping clay content variation using electromagnetic induction techniques. Comput. Electron. Agric. 46, 203–237.

Triantafilis, J., Laslett, G.M., McBratney, A.B., 2000. Calibrating an electromagnetic induction instrument to measure salinity in soil under irrigated cotton. Soil Sci. Soc. Am. J. 64, 1009–1017.

Triantafilis, J., Odeh, I.O.A., Jarman, A.L., Short, M.G., Kokkoris, E., 2004. Estimating and mapping deep drainage risk at the district level in the lower Gwydir and Macquarie valleys, Australia. Aust. J. Exp. Agric. 44, 893–912.

Zhu, Q., Lin, H., Doolittle, J., 2010. Repeated electromagnetic induction surveys for improved soil mapping in an agricultural landscape. Soil Sci. Soc. Am. J. 74, 1763-1774.