MONITORING SPATIAL VARIATION OF SOIL MOISTURE IN CROP FIELDS WITH EM38

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ABSTRACT

Electromagnetic induction (EMI) technique is currently available as a commercial equipment to measure apparent electrical conductivity (EC_a) of soils as a non-contact method by using EM38. A Field experiment with wheat was conducted to investigate the effects of variation in soil water and temperature (i.e. soil and air) on the EM38-measured EC_a in vertical and horizontal modes of operation. Additional measurements were made to study the effects of placing EM38 at various heights above the ground (0.1 and 0.4 m) on EC_a. We used an EM38 and a neutron probe to measure EC_a and profile soil water content, respectively within top 1.33 m of soil in 3 replicated plots of 4 irrigation treatments. Irrigation treatments (T50-T85) were designed to allow soil water depletion down to 50%, 60%, 70% and 85% of the plant available water capacity in soil. During EM38 survey, we also recorded the locations of all measurements with a hand held GPS. Air temperature and soil temperature at 5, 10 and 25 cm depths was recorded for all the 12 plots during EM38 survey.

Results indicated spatial variation in the soil water in the field to be detected well with EM38 measurements. Significant effects of soil water was observed on all EC_a measured with the EM38 probe. Soil water content within the shallow and deep parts of the crop root zone could be explained by the measured values of EM38 at multiple depths above the ground. The coefficient of determination (R^2) for regression models used to describe the relationship between EC_a and soil water content was larger for horizontal mode than vertical mode of operation. Both soil and air temperature also had significant effects on measured EC_a. Overall, EM38 was found to be quite easy to use and helpful for monitoring spatial variation of soil water content in the field. Similarities in the pattern of spatial variation in soil water and EC_a over the entire crop field observed in our study suggests that this technique can be used successfully to determine soil water deficit in clay soils such that precise and variable quantity of irrigation water can be delivered to crops at various parts over the same crop field.

INTRODUCTION

Increasing 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). Grid mapping is generally regarded as one of the more accurate ways to map a field in detail (Buol et al. 1997). However, grid mapping is time consuming and expensive because of the time and labour involved to create accurate grids in the field (Brevik et al. 2003), making it desirable to find other, more rapid means of obtaining information for detailed soil mapping. In-situ measurement of apparent electrical conductivity (EC_a) in the field has generated considerable interest over time as a potential technique in many soil applications as EC_a can be used as a surrogate variable to infer other soil properties. Electromagnetic induction (EMI) is a non-

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invasive technique that allows measurement of apparent soil electrical conductivity (EC_a) by inducing an electrical current in the soil. A transmitter located at one end of the electromagnetic (electrical conductivity) instrument induces circular eddy current loops in the soil. The magnitude of these loops is directly proportional to the conductivity of the soil in the vicinity of that loop. Each current loop generates a secondary electromagnetic field which is proportional to the value of the current flowing within the loop. A fraction of the secondary induced electromagnetic field from each loop is intercepted by the receiver coil and the sum of these signals is amplified and formed into an output voltage which is linearly related to depth-weighted soil EC_a (Rhoades 1992). EMI has several, known advantages over other methods which include avoidance of use of radioactive sources (e.g. use of a neutron source in a neutron moisture meter) and speed and ease of use due to its portability and non-invasive nature (Reedy and Scanlon 2003). For these reasons, EMI technique has been developed to enable rapid and repetitive monitoring of a large number of sites over an extended period in both fallow and cropped fields.

Measurements of EC_a of soil with EM38 (based on the EMI technique) have received considerable interests from the precision agriculture community (Corwin and Plant 2005; Fritz et al. 1999). The parameters which dominantly influence EC_a are soil salinity, clay content and clay mineralogy, soil moisture and soil temperature (Friedman 2005; James et al. 2000; McNeill 1980a). EC_a data can be used to indirectly estimate soil properties if the contributions of other soil properties affecting the EC_a measurement are known or can be estimated. Previous studies have found good correlation between clay content and soil electrical conductivity measurements by EM38 (Dalgaard et al. 2001; Hedley et al. 2004; Triantafilis and Lesch 2005). This technique has been also used to study variations in soil depth (Bork et al. 1998), soil type (Greve and Greve 2004), 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; Jaynes et al. 1995). Various aspects of soil water content and its relationship with EC_a has been studied at various spatial scales (Kachanoski et al. 1988; Kachanoski et al. 1990; Khakural et al. 1998; Morgan et al. 2000), but few studies have attempted temporal variation in water content. At a given location, EC_a can vary with changes in soil moisture content (Brevik et al. 2006). Brevik & Fenton (2002) found soil moisture to be the single most important edaphic factor among others (e.g., soluble salts, clay content and soil temperature) that influenced EC_a determination. This study was conducted to identify:

- the effects of variation in soil moisture content on apparent electrical conductivity of soil (EC_a) measured with EM38 in both vertical and horizontal mode;
- the effects of placing EM38 at various heights above the ground on EC_a;
- the effects of variation in air and soil temperature on EC_a.

MATERIALS AND METHODS

This study was conducted in an experimental field for wheat (*Triticum aestivum* L.) at Kingsthorpe Research Station of the Queensland Primary Industries and Fisheries (now referred to as the Department of Employment, Economic development and Innovation) near Kingsthorpe (27°30 '44"S, 151°46'55"E, and 431 m elevation). The soil at this site was a haplic, self-mulching, and black vertosol (Isbell, 1996). The field experiment consisted of four irrigation treatments and three replications of each treatment using a randomized block design.

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Each replicate plot had a dimension of 13 m × 20 m, which was separated from adjacent plots with 4 m wide buffer. Wheat was sown at a depth of 50-75 mm on 6th June 2008. The crops emerged 10 days after sowing. At sowing 174 kg ha^{-1} of urea and 230 kg ha^{-1} of mono ammonium phosphate was applied to all the experimental plots. The aim for planting density was 200 plants m^{-2} and the actual planting density was 220 plants m^{-2} with a row spacing of 25 cm. For weed control 500 ml ha^{-1} of Starane 200 was applied on 1st July 2008 and additional 1 l ha^{-1} of Starane was applied on 22nd July 2008. Additional 100 kg N ha^{-1} was applied when the first node of wheat plant was visible.

Irrigation was imposed within the experimental area when plant water available capacity (PAWC) depleted to 50%, 60%, 70% and 85% (denoted as T50, T60, T70 and T85, respectively). Each replicate plot was irrigated with bore water using a hand-shift solid sprinkler system. Partial-circle sprinkler heads were used to avoid irrigation of adjacent plots. In order to monitor soil water content within experimental plots over time, neutron access tubes were installed in the centre of each plot. A neutron probe (503DR Hydroprobe, Campbell Pacific Nuclear Inc., Martinez, CA, USA) was used to measure soil water content from surface to a depth of 1.33 m at 0.1 m depth increments. The neutron count ratio (n) was converted to volumetric soil water content (θ, m^3 m^{-3}) using the calibration equation:

$$\theta = 1.36\ n - 0.44. \qquad (R^2 = 0.86) \qquad (1)$$

Measurements

EM38 survey was done during the growing season for wheat crop in 2008. The EM38 (Geonics Limited, Mississauga, Ontario, Canada) instrument 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 could be operated in one of the two measurement modes. In the vertical mode (VM) of EM38, the measured values of EC_a is known to be a function of the soil properties within a depth of about 1.5 m, while in the horizontal mode (HM) EC_a corresponds with soil properties within 0.75 m depth (McNeill, 1980b). EM38 has considerably greater application for agricultural purposes because the depth of measurement corresponds roughly with the root zone of most agricultural crops when the instrument is placed in the vertical coil configuration mode (Corwin and Lesch 2005). EM38 survey was done in both VM (Fig. 1) and HM (Fig. 2) at the centre of each plot (i.e. 3 m from the neutron access tubes) on the ground for 12 occasions (i.e. 13, 19, 28, 35, 56, 63, 70, 80, 105, 112, 131 and 145 DAP) during the wheat season.

On all occasions, EM38 was first calibrated and nulled according to the manufacturer's instruction before starting a measurement. Continuous proximal sensing, often referred to the electromagnetic induction sensing of soil electrical conductivity, together with precise global positioning systems (GPS) have enabled accurate mapping of within-field soil variability that can help site specific management (Plant 2001). This requires location of each EM38 measurement in the field to be recorded with a hand held GPS. As it has been reported that ambient air temperature can influence EC_a readings collected with the EM38 (Sudduth et al. 2001), air temperature was recorded with an Omega type RTD probe during the EM38 survey of each experimental plot. Some studies have shown that changes in temperature over time period of several weeks to months can significantly influence EC_a readings of EM38 (Brevik and Fenton 2002; Nugteren et al. 2000; Sudduth et al.

2001). This is due to the dependency of soil electrical conductivity on soil temperature that varies seasonally due to the variation in air temperature (Huth and Poulton 2007).

Figure 1. Operation of EM38 in vertical mode (VM) at the soil surface in the wheat field.

Figure 2. Operation of EM38 in horizontal mode (HM) at the soil surface in the wheat field.

Variation in soil temperature is usually greater near the soil surface (i.e. at shallow depths of 5 and 10 cm) than at greater depths (e.g. 30 cm) with little or no change at depths below 60 cm (Jury et al., 1991). Therefore soil temperature was measured with the RTD probe at 5, 10 and 25 cm depths by pushing the tip of the temperature probe to the appropriate soil depth. These soil depths were chosen primarily to represent temporal variation in soil temperature in the field during EM38 measurement. Measurement of soil temperature at shallow depths (i.e. 5 and 10 cm) was time consuming because the probe required longer time period (2 to 3 min) for readings to stabilise than for measurement of soil temperature at 25 cm depth. When the soil was dry, it was difficult to push the temperature probe into the ground. A stainless steel rod with a conical tip was first pushed into the ground to make a pilot hole a depth few mm lower than the desired depth. Then the temperature probe was inserted to the desired depth to measure soil temperature. Both soil and air temperature was measured on 10 occasions (i.e. 13, 19, 28, 35, 56, 63, 70, 105, 131 and 145 DAP) for the entire wheat season. It has been shown previously that EC_a measurements with EM38 are strongly influenced by the distance of EM38 probe from the ground level, i.e. when EM38 is placed at some height above the ground (Sudduth et al. 2001). To gain further insight into the response of EM38 to variation in soil water content at various depths, additional measurements with 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. 56, 63, 70, 105, 131 and 145 DAP). To facilitate the EM38 measurement at desired heights above the ground a wooden frame with a platform was used (Fig. 3).

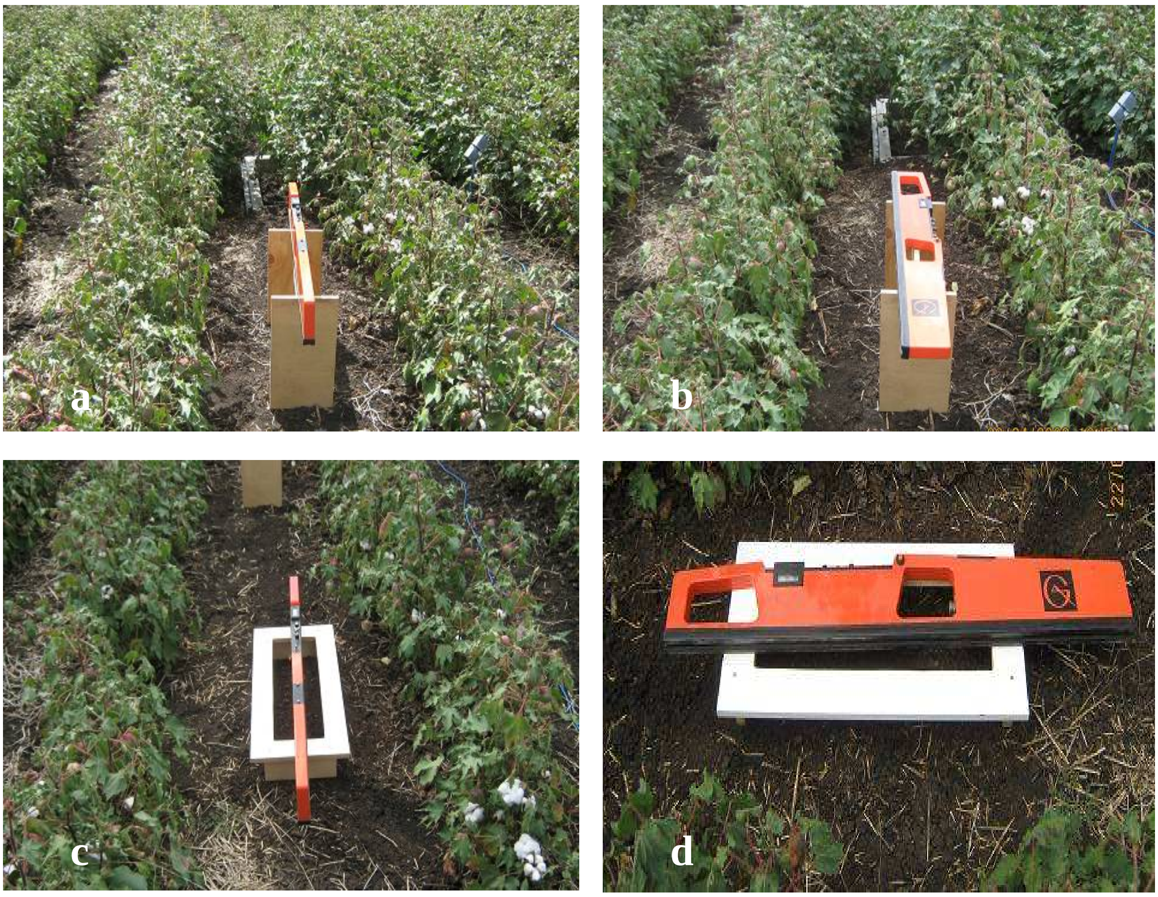

Figure 3. EM38 measurements at various heights above the ground shown for a cotton field. (a) VM – 0.4 m height, (b) HM – 0.4 m, (c) VM – 0.1 m and (d) HM – 0.1 m.

Raising the EM38 above the ground is equivalent to shunting or lowering of the EM38 depth-response function, i.e. in the vertical mode, an EM38 reading at 0.1 m above the ground is expected to represent EC_a within1.4 m soil depth and at 0.4 m above the ground within 1.1 m soil depth. In a similar way, measurements in the HM at 0.1 and 0.4 m height above the ground, the effective soil depth of measurement could be reduced to 0.65 and 0.35 m, respectively. A neutron probe was used to measure soil water content from 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 that was close to the effective depth of sensing of EM38 probe. Measurements 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 with the estimated soil water content (mm). Since soil water content was measured to a maximum depth of 1.33 m, EM38-measured values of EC_a was correlated with this water content in VM of EM38 at the ground level as well as at 0.1 m height above the ground.

RESULTS AND DISCUSSION

Effects of soil water content on EC_a

Variation in EC_a with variation in soil water within the top 1.33 m soil is shown for combined irrigation treatments of wheat in Fig. 4 for the vertical mode measurements of EM38. Dashed line represents the linear regression equation fitted to these data as $y = 0.54\,x – 135.54$ (n = 144, R^2 = 0.70, P≤0.001), where y = EC_a in mS m^{-1} and x = soil water in mm. It can be seen from Fig.4 that this linear regression equation did not fit well to these data for wet soil conditions with soil water > 550 mm possibly because the effective response depth of EM38 in vertical mode is 1.50 m that did not match well with soil water represented within 1.33 m soil depth. Therefore a nonlinear equation was fitted to these data (represented by a solid line in Fig. 4) as $y = 211.76\,[1 – 16.01\,e^{-0.0077\,X}]$ (n = 144, R^2 = 0.77, P≤0.05), that represented the data better than the linear regression. Soil water within 1.33 m depth for various irrigation treatments was in the range of 460 – 660 mm for T50, 440 – 540 mm for T60 and T70, and 400 – 525 mm for T85. All plots under T50 were irrigated most frequently and T85 least frequently.

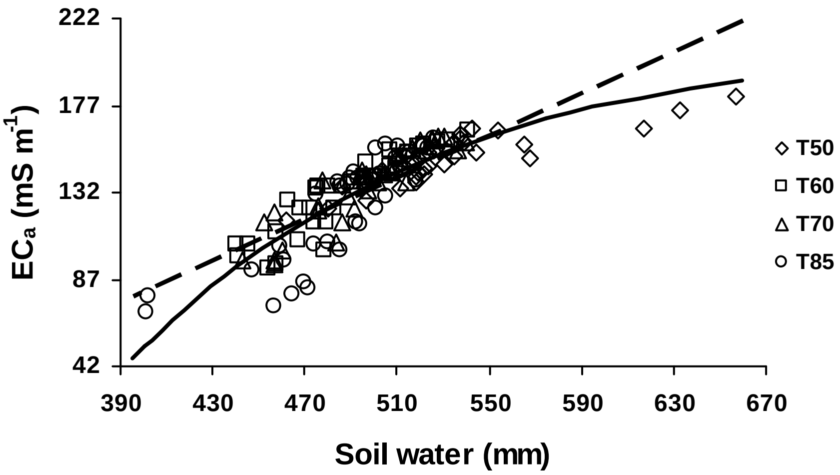

Figure 4. The relationship between water content within the top 1.33 m of soil and EC_a measured in the vertical mode for various irrigation treatments.

Although the depths used for soil water content and EC_a with EM38 were different, in Fig. 4, these trends suggest that a departure from linearity in the response of EM38 may occur for very wet soils or fields receiving more frequent irrigation to maintain low soil water deficit. Similar measurements of EC_a in the horizontal mode of EM38 have been plotted against soil water within 0.73 m depth (Fig. 5). An equation $y = 0.0007\ x^{2.1163}$, (n = 144, $R^2 = 0.78$, $P \leq 0.001$) fitted to these data are shown as a dashed line in Fig. 4. Note that the data range when relating EC_a in HM with soil water content was less than that shown Fig. 4 as EC_a responds to soil water within a shallower depth of 0.75 m. EC_a measured in the HM also increased with increase in soil water content although the dashed line did not appear to represent the data well at high soil water content as in the VM of EM38. These data could be best represented with a nonlinear equation of the type $y = 202.46\ [1 – 3.369\ e^{-0.0071\ x}]$ (n = 144, $R^2 = 0.76$, $P \leq 0.05$).

Brevik et al. (2006) investigated the effects of variation in soil water content on EC_a with EM38 on five different types of soil in both vertical and horizontal mode for grassed and non irrigated condition. Huth and Poulton (2007) used electromagnetic induction method for monitoring variation in soil moisture in agroforestry systems. Studies regarding the effect of soil water content on EC_a measurement of EM38 under irrigated condition were limited. Therefore this experiment was conducted in order to investigate the effect of soil water on EC_a measurement of EM38 for both vertical and horizontal mode.

In order to study the variation in EC_a and its response to soil water content when EM38 is placed at some height above ground, values of EC_a for VM at 0.1 and 0.4 m height above the ground were plotted against soil water in the top 1.33 and 1.13 m (Fig. 6 and 7). Although variation in soil water was the same as for Fig. 4, a change in the range of EC_a values obtained (57-172 mS m^{-1}) compared with 70-182 mS m^{-1} obtained for VM of EM38 earlier showed a linear increase in EC_a with increase soil water content. These results suggest that EC_a measured in VM at 0.1 m height above the ground represented soil water within 1.33 m depth much closely with a higher degree of precision.

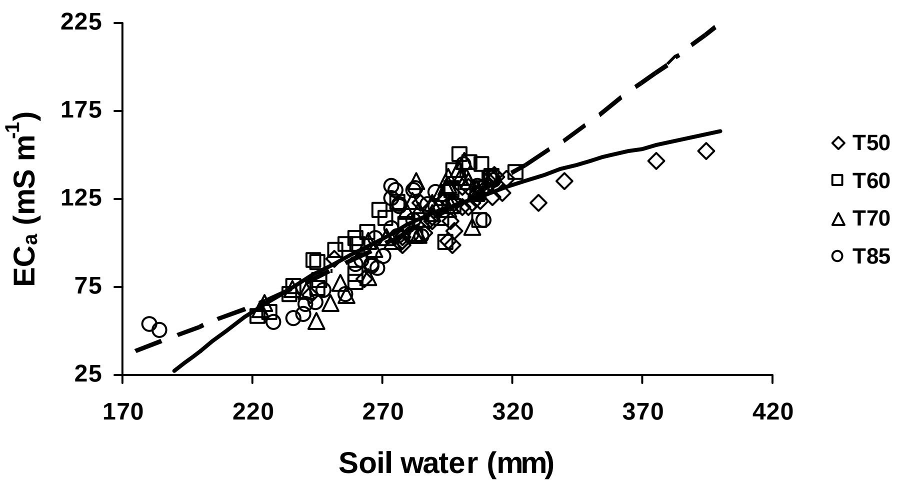

Figure 5. The relationship between water content within the top 0.73 m of soil and EC_a measured in horizontal mode for various irrigation treatments.

Similar linear relationships were also found with measurements of EC_a in the vertical mode of EM38 when the instrument was placed at 0.4 m height above the ground (Fig. 7) although the range of soil water content (320-575 mm) and EC_a (50 to 140 mS m^{-1}) were both reduced considerably due to a reduction in the effective response depth of EM38. These results collectively indicate that placing EM38 at various heights above the ground, it is possible to estimate and/or predict soil water content at various soil depths in the vertical mode of EM38.

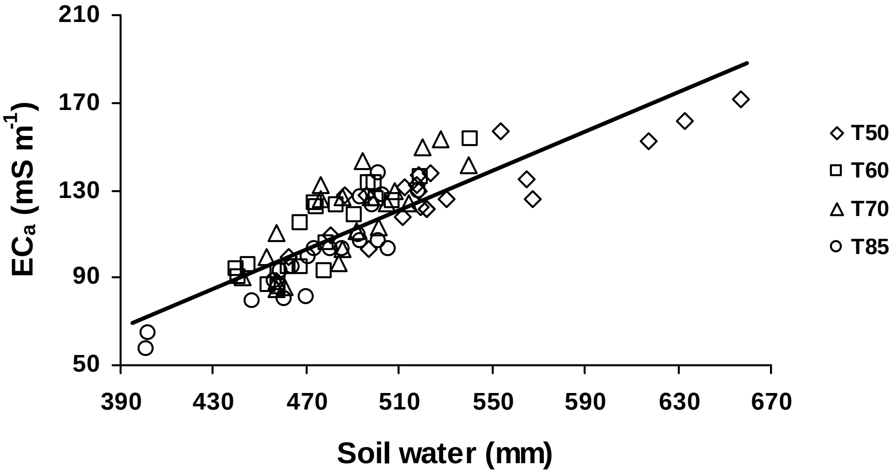

Figure 6. The relationship between water content within the top 1.33 m of soil and EC_a measured in vertical mode at 0.1 m height above the ground for various irrigation treatments.

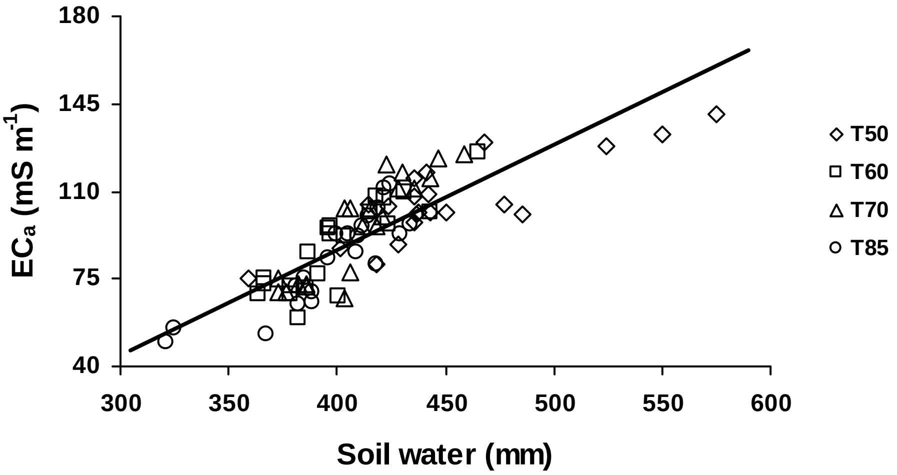

Figure 7. The relationship between water content within the top 1.13 m of soil and EC_a measured in vertical mode at 0.4 m height above the ground for various irrigation treatments.

EC_a values at 0.1 and 0.4 m height above the ground in HM were also plotted similarly against soil water within the top 0.63 and 0.33 m, respectively (Figs. 8 and

9). The amount of soil water varied from 145–345 and 45–180 mm for 0.1 and 0.4 m height above the ground, respectively. Values of EC_a in HM appeared to decrease more rapidly with height above ground than did in the VM due to the difference in effective response depth that represented less soil water. In this situation, EC_a changed linearly with soil water when EM38 was placed at 0.1 m height above the ground, but exponentially when it was placed at 0.4 m height above the ground. 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 height above the ground in HM of EM38. The statistics of the regression equations representing the general relationship between the plotted variables in these figures are given in Table 1. The coefficient of determination (R^2) indicates the extent to which the variation in the plotted data is represented by the regression while the probability (P-values) of the fitted coefficients (slope and intercept terms) are obtained with analysis of variance to represent the degree of confidence. Data in Table 1 indicated R^2-values to be higher with EC_a measured in HM than VM. Improvements in regression with HM over VM could be due to higher contribution of upper soil layers near the surface to measured values of EC_a than the lower soil layers that supports the earlier assertion of McNeill (1992) that contribution of various soil layers to EC_a decrease exponentially within the effective soil depth of 0.75 m. Therefore, EM38 readings would be expected to be more strongly and closely related with soil water content near the surface. The ability of EM38 to predict soil water near the surface with high accuracy observed in our study suggests that EM38 in horizontal mode will allow good representation of temporal changes in soil water content in the surface soil layers of irrigated crop fields, where most changes are likely due to irrigation and evapotranspiration. Overall, there was a significant effect of soil water on EC_a. Sudduth et al. (2001) has used an automated system positioned the EM38 around 20 to 22 cm above the ground surface but this height may vary due to bouncing of EM38 trailer when travelling across rough areas especially at high speeds and also introduce errors in readings of EC_a measurement of EM38 and this study was conducted for grassed condition. But in this experiment measurement of EM38 was conducted at various heights under irrigated and cropped condition.

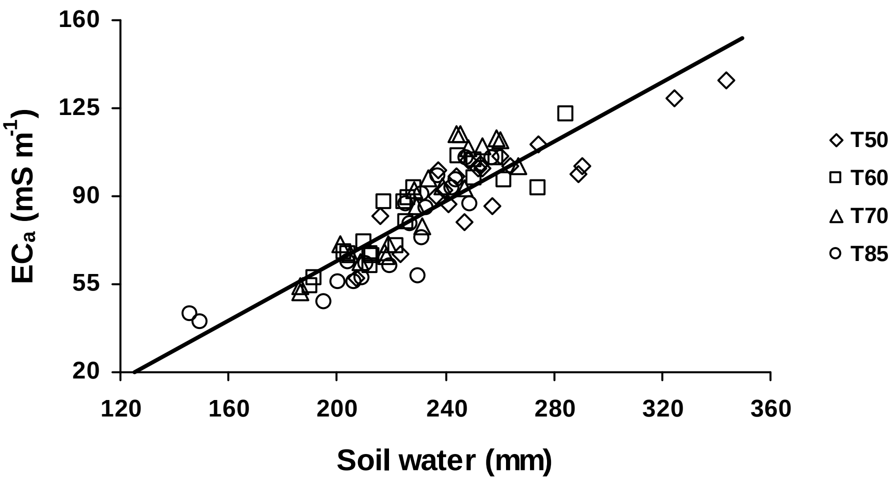

Figure 8. The relationship between water content within the top 0.63 m of soil and EC_a measured in HM at 0.1 m height above the ground for various irrigation treatments.

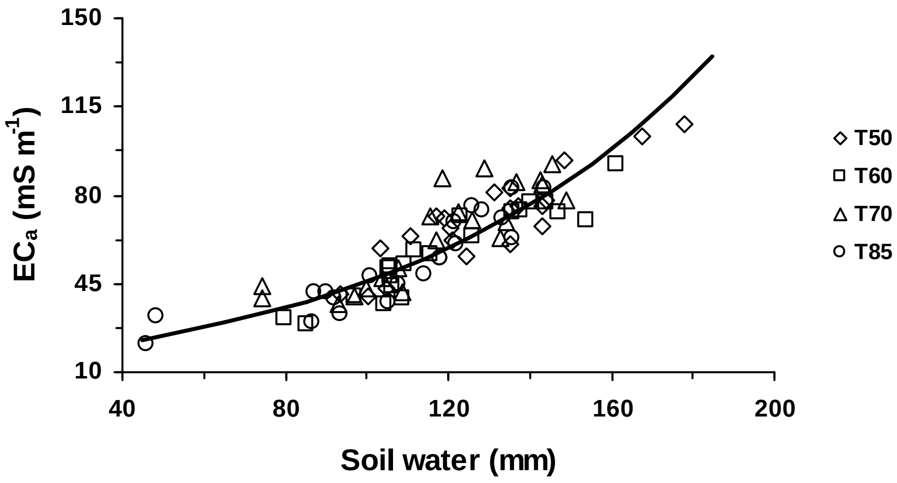

Figure 9. The relationship between water content within the top 0.33 m of soil and EC_a measured in horizontal mode at 0.4 m height above the ground for various irrigation treatments.

Table 1. Regression equations, coefficient of determination (R^2) and probability of significance (P-values) for the relationships between EC_a (y, mS m^{-1}) and soil water (x, mm) for various irrigation treatments in VM and HM of EM38 at 0.1 and 0.4 m above the ground. No. of data points (n) used was 84 for P ≤ 0.001.

Height above ground (m)	Mode of operation	Regression equation	R^2
0.1	VM	$y = 0.45\ x - 108.67$	0.70
	HM	$y = 0.59\ x - 53.47$	0.78
0.4	VM	$y = 0.42\ x - 81.77$	0.71
	HM	$y = 12.9162\ e^{0.0127\,x}$	0.81

Effects of temperature on EC_a

In order to determine the effects of temperature on EC_a, air temperature and soil temperature at 5, 10 and 25 cm depths, simple linear regression models were used. Regression equations and associated values of R^2 and P for both VM and HM of EM38 are given in Tables 2 and 3. Although fitted regression equations were all highly significant (P<0.001) due to the amount of data (n = 120) used, low R^2 values (0.27-0.36 for VM and 0.29-0.43 for HM) obtained with these regression models suggest that there was a linear dependency of EC_a on temperature, but the degree of scatter of data (evident from Fig. 4) for EC_a in VM against soil temperature at 10 cm depth) suggest that the contribution of temperature to EC_a was much smaller than that due to the variation in soil water. Previous studies on the effects of soil temperature on EC_a on a variety of landscapes using EM38 are limited for irrigated condition and also did not measure the soil temperature during dry condition (Brevik and Fenton 2002; Nugteren et al. 2000; Sudduth et al. 2001).

Table 2. Regression equations, coefficient of determination (R^2) and probability of significance (P-values) for the relationship between EC_a (y, mS m^{-1}) and temperature (both soil and air, x, ℃) for various irrigation treatments in VM of EM 38. No. of data points (n) used was 120 for $P \leq 0.001$.

Temperature	Regression equation	R^2
Air	$y = -1.95\ x + 182.73$	0.27
Soil – 5 cm	$y = -2.05\ x + 173.45$	0.31
Soil – 10 cm	$y = -2.55\ x + 176.69$	0.37
Soil – 25 cm	$y = -3.48\ x + 192.17$	0.36

Table 3. Regression equations, coefficient of determination (R^2) and probability of significance (P-values) for the relationship between EC_a (y, mS m^{-1}) and temperature (both soil and air, x, ℃) for various irrigation treatments in VM of EM 38. No. of data points (n) used was for 120 $P \leq 0.001$.

Temperature	Regression equation	R^2
Air	y = -2.31 x + 166.40	0.29
Soil – 5 cm	y = -2.46 x + 156.12	0.34
Soil – 10 cm	y = -3.14 x + 161.36	0.43
Soil – 25 cm	y = -4.36 x + 181.68	0.43

Mapping of soil water and EC_a

Since the position of all measurements remained fixed over time and known from the GPS records for all EM38 and water content measurements and that we have shown in previous sections that there was a strong dependency of EC_a on soil water content, it is possible now to compare EC_a maps with soil water maps on a given day of measurement to gain additional confidence on the usefulness of EC_a and its ability to predict soil water content. Figures 10 and 11 show the spatial variation in EC_a measurement in the vertical mode and soil water for all the 12 plots of the irrigation experiment with wheat. Filled circles on the map represent the measurement location for each plot with label denoting irrigation treatment (T50…T85) and replicate (R1…R3). Areas within these maps with a darker shade of grey indicate relatively high value of EC_a that juxtaposes with a similar location in the field of high soil water content within the depth-response range of EM38. In a similar way, areas of lighter shade of grey (almost white) depict low EC_a and soil water content. Since areas of the field with T50 and T85 treatments respectively indicate areas of lowest and highest soil water deficit, frequent mapping of EC_a can be used to apply variable quantities of water to reduce soil water deficit and practice precision irrigation.

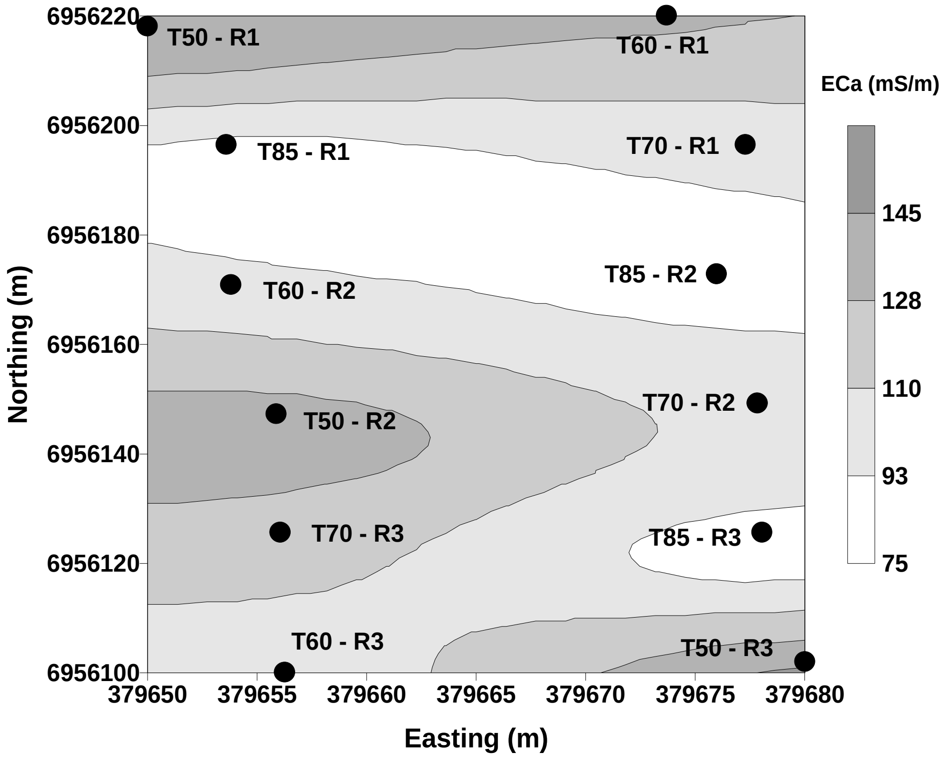

Figure 10. Spatial variation in EC_a at the irrigation experiment site at 131 days after planting wheat. Filled circles indicate the position of measurement for irrigation treatments T50, T60, T70 and T85 and replicates R1, R2 and R3 of each irrigation treatment. The legend bar shows values of EC_a in mS/m.

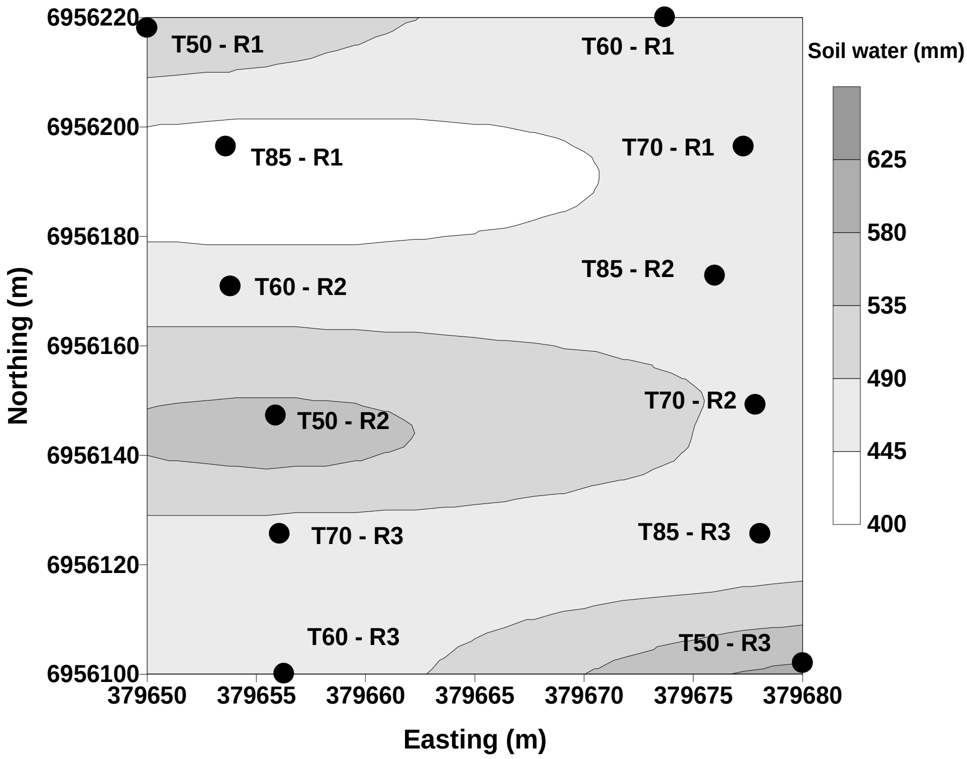

Figure 11. Spatial variation in soil water content within 1.33 m depth for the irrigation experiment at 131 days after planting wheat. Filled circles indicate the position of measurement for each plot of the entire field. T50, T60, T70 and T85 are irrigation treatments and R1, R2 and R3 are replicates of each treatment. The legend bar shows the values of soil water in mm.

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CONCLUSIONS

Simultaneous measurements of soil water content and EC_a measured with EM38 in the field have indicated that for soils of high clay content EM38-measured EC_a can be used for prediction of soil water within the root zone of a range of crops by combining vertical and horizontal modes of measurement supplemented by placing EM38 at desired height above the ground. 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 measurement of soil water content with neutron or other soil water sensors, it may be possible to use this technique with mobile irrigation application systems. Seasonal variation in temperature can influence EC_a significantly, but its overall effects are relatively small. Maps of EC_a can be used to gain information on soil water to practice precision irrigation when spatial variability in EC_a is due to variation in soil water content. If the spatial variation in EC_a in a field is due to spatial variation of a soil property that does not contribute to variation in soil water content, then EC_a map should not be used to predict soil water in that situation.

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REFERENCES

Batte, M. T. (2000). Factors influencing the profitability of precision farming systems. Journal of Soil and Water Conservation, 55, 12–18.

Bork, E. W., West, N. E., Doolittle, J. A., & Boettinger, J. L. (1998). Soil depth assessment of sagebrush grazing treatments using electromagnetic induction. Journal of Rangeland Management 51, 469–474.

Brevik, E. C. & Fenton, T. E. (2002). The relative influence of soil water content, clay, temperature, and carbonate minerals on soil electrical conductivity readings taken with an EM-38 along a Mollisol Catena in Central Iowa. *Soil survey horizons,* 43**,** 9-13.

Brevik, E. C., Fenton, T. E., & Jaynes, D. B. (2003). Evaluation of the accuracy of a central Iowa soil survey and implications for precision soil management. Precision Agriculture, 4, 323–334.

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

Buol, S. W., Hole, F. D., McCracken, R. J., & Southard, R. J. (1997). Soil genesis and classification, 4th edn. Iowa State University Press, Ames, USA.

Corwin, D. L., & Lesch, S. M. (2005). Apparent soil electrical conductivity measurements in agriculture. Computers and Electronics in Agriculture, 46, 11-43.

Dalgard, M., Have, H., & Nehmdahl, H. (2001). Soil clay mapping by measurement of electromagnetic conductivity. Third European Conference on Precision Agriculture. June, 18-20, Montepelier, France, pp.367-372.

Friedman, S. P. (2005). Soil properties influencing apparent electrical conductivity: A review. *Computers and Electronics in Agriculture,* 46**,** 45-70.

Fritz, R. M., Malo, D. D., Schumacher, T. E., Clay, D. E., Carlson, C. G., Ellsbury, M. M., & Dalsted, K. J. (1999). Field comparison of two soil electrical conductivity measurement systems. In: Robert, P. C., Rust, R. H., Larson, W. E. (eds). Proceedings of the fourth international conference on precision agriculture, pp. 1210-1217. ASA, CSSA, SSSA, Madison, USA.

Greve, M. H., & Greve, M. B. (2004). Determining and representing width of soil boundaries using electrical conductivity and MultiGrid. Computers & Geosciences, 30, 569–578.

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. Australian Journal of Soil Research 42(4), 389–400.

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, pp. 144-151, Lake Buena Vista, Florida.

Huth, N. I. & Poulton, P. L. (2007) An electromagnetic induction method for monitoring variation in soil moisture in agroforestry systems. Australian Journal of Soil Research, 45**,** 63-72.

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

James, I. T., Waine, T. W., Brandley, R. I., Godwin, R. J., & Taylor, J. C. (2000). A comparison between traditional methods and EMI scanning for determining soil textural boundaries. Agenda 2000, Warwick, paper no. 00-PA-014.

Jaynes, D. B., Colvin, T. S., & Ambuel, J. (1995). Yield mapping by electromagnetic induction. In: Robert, P. C., Rust, R. H., Larson, W.E. (Eds.). Proceedings of the Second International Conference on Site-specific Management for Agricultural Systems, pp. 383–394. ASA-CSSA-SSSA, Madison, USA.

Jury, W. A., Gardner, W. R. and Gardner, W. H. 1991. Soil Physics, 5th edn (John Wiley and Sons, Inc.).

Kachanoski, R. G., Gregorich, E. G., & Van Wesenbeck, I. J. (1988). Estimating spatial variations of soil water content using non contacting electromagnetic inductive methods. Canadian Journal of Soil Science, 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. Canadian Journal of Soil Science, 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. Communications in soil science and plant analysis*,* 29 (11-14)**,** 2055-2065.

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.

Morgan, C. L. S., Norman, J. M., Wolkowski, R. P., Lowery, B., Morgan, G. D., & Schuler, R. (2000). Two approaches to mapping plant available water: EM-38 measurements and inverse yield modeling. In: Robert, P. C., Rust, R. H., Larson, W.E. (Eds.). Proceedings of the 5th International Conference on Precision agriculture, p. 14. ASA, CSSA, SSSA, Madison, USA.

Nugteren, W. A., Malo, D. D., Schumacher, T. E., Schumacher, J. A., Carlson, C. G., Clay, D. E., Clay, S. A., & Dalsted, K. J. (2000). Hillslope chronosequence of electromagnetic induction readings as influenced by selected soil properties. In: Robert, P. C., Rust, R. H., Larson, W.E. (Eds.). Proceedings of the 5th International Conference on Precision Agriculture, p. 8. ASA, CSSA, SSSA, Madison, USA.

Plant, R. E. (2001). Site-specific management: the application of information technology to crop production Computers and Electronics in Agriculture, 30, 9-29.

Reedy, R. C., & Scanlon, B. R. (2003). Soil water content monitoring using electromagnetic induction. Journal of Geotechnical and Geoenvironmental Engineering, 129(11), 1-12.

Rhoades, J. D., Manteghi, N. A., Shrouse, P. J., & Alves, W. J. (1989). Soil electrical conductivity and soil salinity: new formulations and calibrations. Soil Science Society of America Journal, 53, 433–439.

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.

Sudduth, K. A., Drummond, S. T., & Kitchen, N. R. (2001). Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. Computers and Electronics in Agriculture, 31, 239-264.

Triantafilis, J., & Lesch, S. M. (2005). Mapping clay content variation using electromagnetic induction techniques. Computers and Electronics in Agriculture, 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 Science Society of America Journal, 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. Australian Journal of Experimental Agriculture, 44, 893–912.