Final Report

Biomass Business 4.1.2

Activity 1: Tools for improved water and fertilizer use efficiency

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Tools for improved water and fertiliser use efficiency in crops and pastures

Summary

This activity was designed to take advantage of evolving methods in precision agriculture (PA) that survey crops and pastures for biomass (or yield) and the soil beneath for moisture content. Together; biomass produced per unit of water used, gives a measure of water use efficiency (WUE). So this activity explores the possibility of using PA methods to generate high resolution maps of water use efficiency. This might help farmers find ways of increasing productivity by fine-tuning crop or pasture management based on what they learn overall about how crops respond to water availability over many sub-field sized areas of their farm. Perhaps input efficiencies could be improved by providing more or less fertiliser based on the biomass or water content mapped for each WUE zone in their field.

We were aware that mapping for biomass using crop reflectance was well established, using commercially available instruments like the CropCircle™ or GreenSeeker™. Yield monitoring during harvesting has also become wide-spread. So the numerator of the WUE calculation (productivity) appeared sound, albeit dependent on the accuracy of instruments and survey techniques. However, mapping of water content was very new. This was thought to be possible using electromagnetic induction (EMI) surveys but little beyond a few other research efforts was available. Agriculture consultants in PA, using EMI surveys for soil texture maps, were aware that EMI surveys appeared to reflect soil water content but the strength of the relationship in practice was anecdotal. Therefore this activity became one of several field experiments designed to demonstrate that WUE could be mapped from a) biomass; derived from crops scans and b) water use; derived from multiple EMI surveys (using the Geonics™ EM38 or similar instrument). More fundamental studies to demonstrate just how well EMI surveys correlate to water extraction by a crop were also done to improve confidence in the approach. Furthermore, the methods used by PA consultants to conduct EMI surveys were found to be somewhat awkward to transfer directly to monitor crops for water use and biomass on a frequent basis. Ideas on how this might be improved will be discussed.

The major findings of this research are:

Mapping soil moisture at high resolution using electromagnetic induction (EMI) surveys is possible for broad-acre cropping on non-saline, heavy clay soils. This approach would probably also work for medium clays to loams but unlikely for sands. Site-specific comparisons between neutron probe counts and apparent electrical

conductivity (EC_a) were highly correlated (r = 0.94). Therefore, relative change in root-zone soil moisture of heavy clays can be mapped using paired EMI surveys by determining the site specific change in EC_a (called 'delta EC_a' or 'ΔEC_a') over short periods of a week to a few months, probably even for a few years. This offers two parameters previously unavailable to broad-acre farming: A) Spatial soil moisture potential or 'bucket size' for all locations in the field; this requires an EMI survey when the land is known to be at the full point, after sustained rain or irrigation, and another when an otherwise unlimited crop has removed the plant available moisture. B) Real-time determination of current soil moisture; The change in EC_a between any two surveys gives soil moisture change over that interval, or for any EMI survey of a field where the spatial soil moisture potential has already been determined, gives current moisture level relative to the known 'bucket size'. We envisage farmers could manage their crops responding to prescription maps showing sites with greater potential, irrespective of actual soil moisture (i.e. maximizing good seasons), or respond immediately to match inputs to growth and soil moisture status, i.e. site-specific farming using variable-rate equipment to alter fertiliser or even sowing rate.

The data required to map soil moisture can be collected using standard EMI survey methods common to consultants of precision agriculture. However, current methods require traversing the field with a quad-runner (or four-wheel- drive) and sled; this is impossible when crops are too large or if managers perceive crop damage. Our report discusses alternatives to this. Calibration of ΔEC_a to actual soil moisture content is possible but would require considerable soil-coring for volumetric soil moisture (VMC), seldom done in practice, and argued here to be largely unnecessary for most cropping applications. How high-resolution maps of soil moisture could be used is an open-ended question likely only to be satisfactorily answered by many farmers testing this approach for their particular soils, crop types and management.

This project sought to link EMI soil moisture surveys to those of biomass (from spectral biomass sensing) to generate maps of water use efficiency. Field demonstrations of the techniques were highly informative but of limited success. They taught us that the usefulness of combining biomass and soil moisture maps was highly dependent on the timing and frequency of surveys relative to crop stage and rainfall. The upshot is that high resolution mapping of soil moisture can be achieved via EMI surveys. Only under particular circumstances can these be combined with biomass mapping to provide informative measures of WUE. When achieved this would provide a powerful view of WUE on a spatial resolution not currently available.

Mapping of soil moisture at high resolutions may well assist a multitude of questions way beyond its potential to inform us about water use efficiency. We argue that an inexpensive EMI survey device for widespread use across the grains and pasture industries, easily fitted to common farm vehicles, (like spray-coups and other tractors) and with easy mapping support, is needed to realize the potential suggested by this activity. Only a few immediate uses were identified by our CRCSI commercial partners.

Abbreviations

AOS Active optical sensors, like CropCircle™ and Greenseeker™, measure the ‘greeness’ i.e. chlorophyll density of the sensors view, (about 0.2 of a sq metre but much greater more powerful versions are fitted to aircraft, eg. The UNE Raptor). AOS sensor readings can be related to the amount of green biomass in the sensors view. ‘Active,’ because they have an onboard emitter of red and infrared light, which means they do not rely on the ambient light to make measurements, so can be operated under any light conditions, even at night. ‘Optical,’ because they register wavelengths of light that are in or around the visible spectrum. Note however that much of the infra-red wavelengths are not in the visible spectrum. Multispectral optical sensors register several wavelengths that can be combined to produce vegetation indices that not so sensitive to sensor positioning.

EC Electrical conductivity, measured by placing two metal electrodes into the soil, charging one and measuring the conductance to the other.

EC_a The apparent electrical conductivity. The electrical conductivity of the soil determined by <u>inducing</u> a current in the soil using electromagnets, rather than directly attempting to pass a current through the soil from one electrode to another.

GPS Global positioning systems. Geo-positioning at the earth’s surface by timing signals emitted from a group of orbiting GPS satellites. Differential GPS can now record positions to well within 50cm.

Site-specific Treatment or management of specific positions in a field with inputs like fertiliser, cultivation, sowing density etc. at resolution much finer than the field level. For example applying different rates of fertiliser across a field based on nutrient sampling to provide a grid of say 10m x 10m would be considered site-specific as opposed to applying a common rate across the entire field.

EMI Electromagnetic induction. The induction of an electric current in a conductor by a moving magnetic field. In this case an electric current is used to generate the magnetic field.

WUE Water Use Efficiency: Ratio of plant production to water used. Commonly yield or biomass produced per unit of water used in that production from the soil (as in the case of this report) but the measure of ‘yield’ can be more specifically defined as a particular product or water can be defined as particularly plant transpiration, irrigation inputs or river extraction, for example.

Contents

Introduction

This project had the goal of mapping the water use efficiency (WUE) of broad acre crops at high resolution, taking advantage of evolving methods in precision agriculture that sense biomass (or yield) and soil moisture content.

Mapping WUE requires two inputs; quantity of plant production and the soil moisture used to generate that productivity. This boils down to measuring the change in soil water content for a change in crop biomass, or overall soil water used to generate yield. Typically the units of WUE are (tonnes of product or dry plant material) / (megalitre of water used per hectare) eg. tonnes grain / megalitre of transpiration. If we could measure WUE accurately enough and there exists sufficient variability over short distances (~ 10 to 100m) within fields, this might suggest economic benefits to varying cropping practices over much smaller areas than is currently done in broad-acre cropping.

The biomass of the green, growing stages of pastures and crops is now routinely mapped by scanning with multi-spectral sensors to determine indices like the normalized difference vegetation index (NDVI), registering reflectance in the optical and near infra-red spectrums and usually done from ground-based vehicles linked to accurate and precise global positioning (GPS). Likewise, yield is mapped routinely using yield monitors fitted to harvesters. So measuring crop productivity in a spatial way to supply the numerator of the WUE formula (WUE = production/water use) is already well establish, albeit dependent on the calibration and well managed use of the equipment for accuracy. But a method for supplying the denominator of the WUE equation, in a spatial way, is not readily available. Mapping agriculturally relevant changes to soil moisture at high resolutions in broad acre cropping is new. Therefore, solving the problem of rapidly mapping soil moisture content becomes central to the success of this project.

Journal papers and conference presentations (national and international) have emanated from this activity, particularly from the work confirming the relationship between the measurement of the soil's electrical conductivity as a massive volume (~2 cubic metres) beneath an EM38, and the soil moisture content measured using a neutron probe in the same volume of soil. We have also explored the effects that field -installed aluminium neutron-probe access tubes might have on the EMI surveys. This work was pivotal for securing scientific confidence in the procedures we were developing to measure WUE..

The goal of this research activity was to: Formulate enterprise-relevant, spatially-enabled measures of water and fertilizer use efficiency in crop and animal production, including plant canopy-based indicators of fertility status and biomass, and develop/refine sensors and protocols necessary to acquire these measurements.

This amounted to answering the following question:

What is the most appropriate, descriptor of ‘efficiency’ in water-limited crop production and how may it be measured and managed using remote and/or proximal sensors that account for within-field spatial variability?

Summaries of the three main experiments to demonstrate the measurement of WUE via PA methods are presented in the following section. Where publications describe the research the reader will be referred to those papers, supplied in the appendix, rather than reproduce all the details in these summaries. The field demonstrations of mapping WUE will be presented in much more detail, especially the most recent research trials at Jemalong Station (Twynam Group, nr. Forbes NSW) which has only just been completed.

Final discussion will bring all that we have learned for recommendations on how to better apply these methods for monitoring WUE in crops and pastures.

Publications emanating from Biomass 4.12

Journal Articles:

Appendix 1:A

John N. Stanley, David W. Lamb, Gregory Falzon and Derek A. Schneider. 2014. Apparent electrical conductivity (EC_a) as a surrogate for neutron probe counts to measure soil moisture content in heavy clay soils (Vertosols). *Soil Research* (accepted Jan 2014) CSIRO.

Appendix 1:B

J.N. Stanley, S.E. Irvine, D.W. Lamb and D.A. Schneider. 2013. Effect of Aluminum Neutron Probe Access Tubes on the Apparent Electrical Conductivity Recorded by an Electromagnetic Soil Survey Sensor. *Geoscience and Remote Sensing Letters, IEEE.* 11 (1) 333-336. DOI: 10.1109/LGRS.2013.2257673.

Conference Proceedings:

Appendix 1:C

John N. Stanley, Derek A. Schneider and David W. Lamb. 2012. Site-specific measurements of apparent electrical conductivity (EC_a) correlate to neutron moisture probe counts: Towards the spatial measurement of soil moisture content for precision agriculture. *Proceedings of the 16th Australian Agronomy Conference.* 14th – 18th October 2012. Armidale, NSW, University of New England.

Appendix 1:D

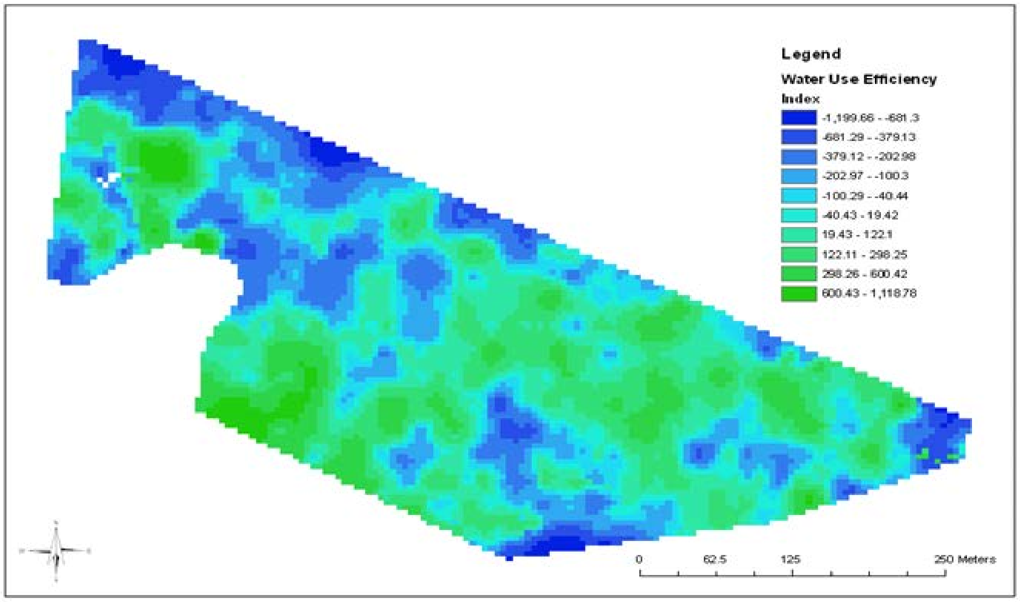
J.N. Stanley, D.A. Schneider, and D.W. Lamb. 2012. Spatial apparent electrical conductivity (ECa), soil moisture and water use efficiency in Vertosol soils. Proceedings of the 12th International Conference on Precision Agriculture. 15th – 18th July 2012. Indianapolas, Indiana. USA.

Please refer to the Appendix at the end of this report for reproductions of these publications.

Summary of the three main experiments

1) Demonstration of mapping water use efficiency by linking spectral scans for biomass with EC_a surveys for soil moisture. Conducted in pasture at McMaster (University of New England Rural Properties), Warialda.
2) Consolidation of the relationship between ΔEC_a and soil moisture. Conducted at the University of New England property, Laureldale and in irrigated cotton at Keytah (Sundown Pastoral Company) nr. Moree.
3) Demonstration of mapping water use efficiency by linking spectral scans for biomass and yield with EC_a surveys for soil moisture. Conducted at Jemalong Station (Twynam Agriculture) nr. Forbes.

1. Demonstration: Mapping water use efficiency by linking spectral scans for biomass with EC_a surveys for soil moisture. Conducted in a wheat crop at McMaster (University of New England Rural Properties), Warialda



Question How good is crop-scanning for biomass and EMI surveys for soil moisture for generating maps of water use efficiency?

Site McMaster Research Station, University of New England, Rural Property nr. Warialda NSW.

Result We were able to produce a map of water use efficiency based on crop scans for changes in biomass (ΔNDVI) and multiple EMI surveys (ΔEC_a) for water use.

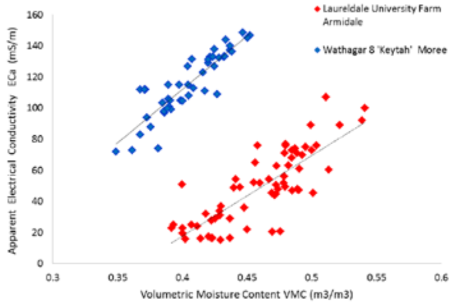
Relevance This showed good promise for producing maps of water use efficiency. The methods included correlations of scans (NDVI) to biomass with plant cuts, and correlations of water use to ΔECa using volumetric water content (VMC). Repeated surveys using the common PA consultants methods of using a quad-runner to scan the crop with a CropCircle (or similar) and towing a Geonics EM38™ (or similar) on a sled were acceptable. Efforts to calibrate the soil water and biomass were laborious and would need to be limited. The interpretation of WUE gained in this way would depend on the timing of surveys relative to rainfall and crop stage. Both the biomass measurement and the soil moisture measurement have limitations that might derail simple interpretations (discussed in detail later in the report). Regular surveys of ΔEC_a are needed to track the moisture changes because rainfall between samples disrupt the sum soil-moisture assumed to be used by the crop in WUE calculations.

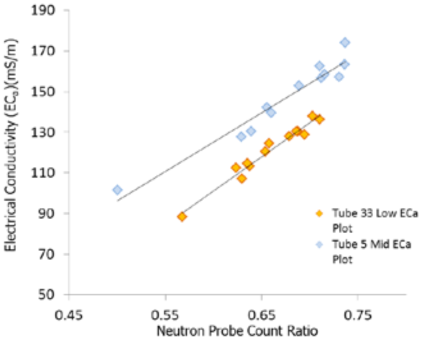
Future

A much larger number of fields need to be surveyed in this way to determine the extent to which WUE is well represented using these methods. The resolution of surveys (width of transects) and accuracy of the measurements needs to be explored to determine the level of effort required to gain most of the information. This will require an economic analysis for a broad range of farming situations.

The current PA survey methods appear most suited to pastures because traversing the fields regularly can be destructive to crops, though surveying at the intensity required to track crop moisture use might be economically prohibitive.

2. ΔECa to soil moisture relationship





Question How well does EC_a measured with an EMI survey device represent soil moisture extraction?

Sites Laureldale Research Station, University of New England, Rural Property Armidale, NSW.

Keytah, Sundown Pastoral. Commercial cotton production nr. Moree NSW. CRCSI Commercial Partner.

Result Repeated measures at Laureldale and Keytah compared volumetric moisture content (VMC) to EM38 (EC_a) readings. This produced good calibrations between EC_a and soil moisture content. The soil types (both heavy clays) at Laureldale and Keytah gave different linear calibrations but provided confidence that perhaps a single slope might be useful for many farms and soils.

This was followed-up with site-specific correlations between a neutron probe and EM38 at 30 sites at Keytah. We were able to relate ΔEC_a of stationary positioning of an EM38 to a standard measure of soil moisture content (r = 0.94). Again, this produced a straight line from wilting point to full point for practical purposes but different sites in the field have different linear relationships (different slopes and intercepts), indicating that for each site or soil 'type or zone' (dependent on background clay content, salinity level, compaction level etc.) a different formula was needed. This was simplified however by recognising that for each position only a full (field capacity) and empty (low plant available water, PAW) reading would be needed. From surveys at these soil moisture levels all near-future soil moisture contents can be determined by a single EMI survey. The EMI survey device registered the best correlation when held 20 cm above the soil surface but the relationship was reasonably strong ($> r = 0.80$) even when held up to 1.2 m above the soil.

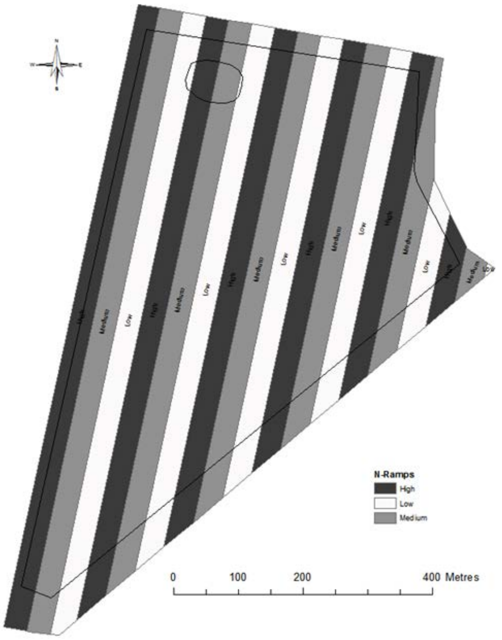
Relevance

This greatly increased our confidence that ΔEC_a from EMI surveys was representing, almost exclusively, soil moisture in the root-zone. It showed that despite this indirect measure of soil moisture all other influences (clay content, salt content and even temperature) were sufficiently small or site-specific for the soil's short-term change in electrical conductivity to mean a change in soil moisture content. Note, however that this was done on a deep, non-saline clay, with good quality irrigation water and with more accurate EM38 calibration than is commonly done in practice. i.e. This is a best-case scenario. Never-the-less we can now be much more confident that EMI surveys over short time periods (weeks or months) reflect strongly changes to soil moisture for clays. Good correlation, even at 1.2 metres provides scope to survey the crop causing less damage.

Future

The range of soils that can be surveyed in this way for soil moisture needs to be assessed. We are confident that sandy soils are not suitable from observations at Jemalong station where both wet and dry sands were indistinguishable using the EM38. We conclude that there will be an intermediate clay content for which soil moisture readings become sufficiently precise. The current EMI survey methods, using a quad-runner plus EM38 sled, is not very suitable for water measurement on crops at the intensity that will be needed to accurately track soil moisture for WUE. A cheaper and farm-vehicle-mounted EMI survey device will be needed.

3. Using PA biomass and soil moisture maps to determine optimum in-season fertiliser rates for a commercial wheat crop at Jemalong Station.



Question	Can PA survey methods of biomass and soil moisture guide variable rate fertiliser use?
Result	Both biomass and soil moisture content can be tracked using PA methods. Unfortunately the limiting factor for this crop was frost rather than water content, so the overall result was inconclusive. Never-the-less biomass correlated reasonably well with soil moisture change over important growth stages. The EMI surveys determined that some areas of the field registered only half the moisture content of others.
Relevance	A farmer taking current biomass and soil moisture levels into consideration for in-season fertiliser management may be in a position to increase average yield or protein levels in their crops using water use and biomass surveys. This is not quite the same as responding to WUE but the same two surveys may still combine to inform crop practices. Regular traversing of the field with common PA survey methods was disturbing to the crop and farmer raised concerns that these were not acceptable in practice. If the crop had been limited by soil moisture, we

would have expected the measure of WUE to be useful for determining optimum fertilizer rates for in-season application.

Future

Many more fields need to be assessed in this way to increase the sample size. We envisage that from many fields the true spatial variation in WUE would be revealed allowing us to better assess the extent to which surveys of this kind can be used to optimise productivity. With a much larger data set, the economic merits of site-specific farming based on biomass and soil moisture surveys could be properly accessed. What is needed is a less disruptive and far cheaper method of doing EMI surveys.

Experiments in greater detail where not produced in publications.

Stage 1: Warialda Experiment: Can PA surveys of ΔBiomass and ΔEC_a be combined to give a map of WUE?

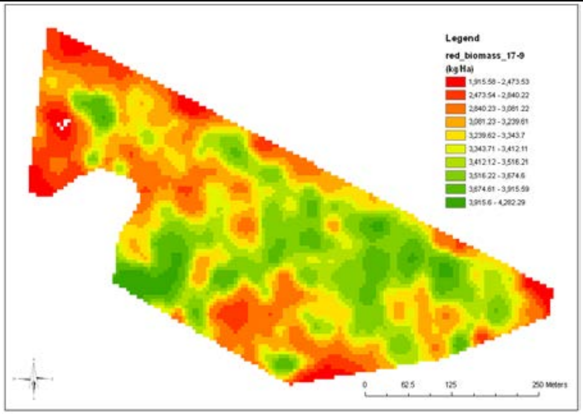
Aim

The experiment at Warialda on a wheat crop represents our first attempt to used PA surveys to determine water use efficiency spatially (WUE). Surveys of biomass (CropCircle™) and soil conductivity (Geonics EM38™) were carried out in conjunction with direct measurements of biomass from crop-cuts and for soil moisture content from volumetric moisture content (VMC) to calibrate each survey. Note that stationary measures of soil conductivity (EC_a) were also measured to closely link EC_a to VMC for soil moisture calibration. This experiment was presented at the International Conference in Precision Agriculture, Indianapolis, July 2012: Appendix 1:D.

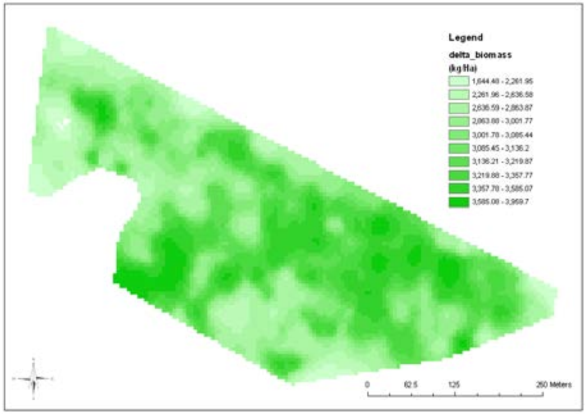
Methods

Plant production measured as change in NDVI and crop water use measured by volumetric moisture content (VMC) from soil cores. ΔEC_a determined between subsequent EMI surveys and related to biomass production predicted by the CropCircle™.

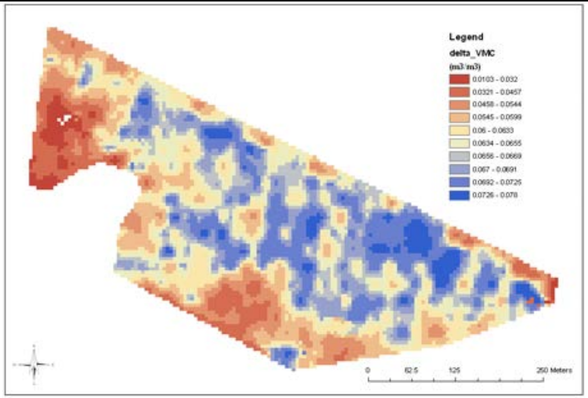
An 18 ha field approximately 35km North of Warialda, NSW (McMaster Research Station,) was the site for EMI and crop circle surveys, along with soil coring for calibration with volumetric water content (VMC). The field was sown to Gregory wheat (*Triticum aestivum var. Gregory*) on the 15th June 2009 along with a uniform application of 65kg/ha anhydrous ammonia and 50kg/ha starter fertiliser (Supreme Z). The starting survey was performed on 4th August 2009 (crop stage Z30) and the end-point survey on 17th September 2009 (Z55). The same Geonics™ EM38 was used in both surveys in the vertical dipole. Reflectance in the red and yellow bands was recordeded using a Holland Scientific CropCircle™. Three crop cuts were taken at 8 sites to generate a calibration curve of biomass (dry weight from 40°C) to reflectance. Soil cores of (3cm dia.) were taken at 4 sites selected to cover the range of apparent electrical conductivity (EC_a) at this site based on a previous EM38 survey. Soil coring to determine volumetric moisture content were taken to one metre, divided into 20cm sections and dried at 110˚C. For calibration with EC_a, stationary (non-survey) EM38 values were recorded at each coring site prior to core removal. After each EM38-Crop circle survey the same core sites were used to create ΔVMC to ΔEC_a correlations. EM38 calibration was performed using the Q-coil described earlier 1. Finally we correlated the grain yield map with the WUE index to determine whether the WUE over the 6 week growth period from stages Z30 to Z55 was a key driver of grain yield.



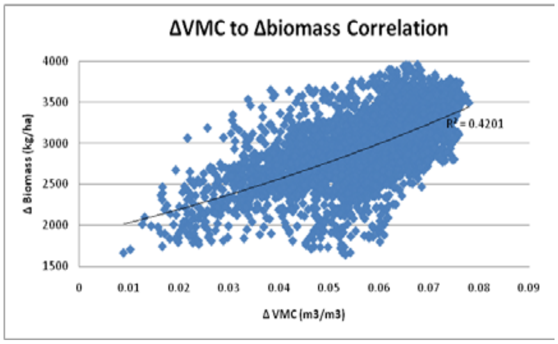
A) Biomass of field from CropCircle (red).



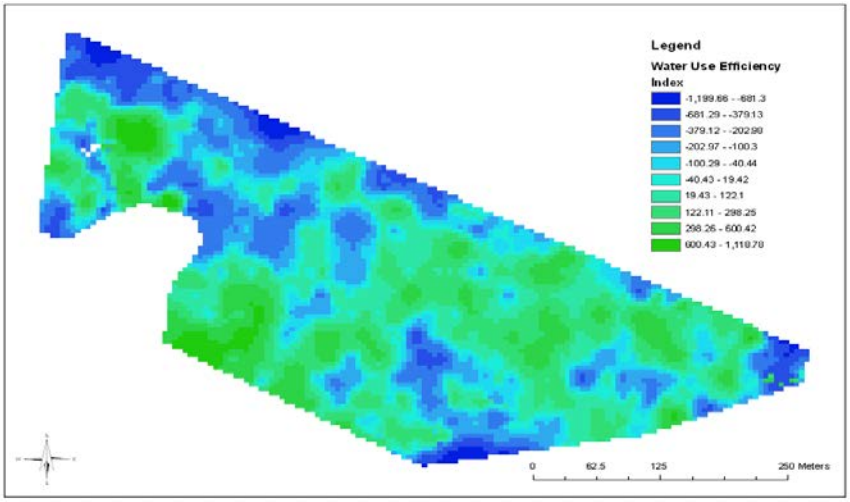
B) Δbiomass map of field from CropCircle (red)



C) Moisture change of field from ΔEC_a



D) ΔVMC to Δbiomass correlation



E) Water Use Efficiency (Δbiomass/ Δwater use) of wheat at McMaster Station.

Unlike a calibration for biomass a single survey cannot be used to correlate EC_a to VMC. The change in EC_a between two surveys is needed. Also, since surveys are done on parallel transects 20 to 50 m apart, rather than measuring every square metre of field, the values for the areas between the transects need to be estimated. These are determined in by kreiging, a method that weights the interpolated values (in this case EC_a) according to the values and distance of many neighbouring measurements. An average value for biomass and moisture for each 5 x 5 m pixel can then be generated and used to map WUE (Δbiomass/ Δwater use) across the entire field.

Conclusion

Surveys at relatively early stages of the crop can be conducted using a quad-runner and sled. Data can be collected on loggers and processed relatively easily by global information systems (GIS) software. The limitations with this approach emerged when trying to interpret the maps. Between any two survey dates we gain a measure of change in biomass and change in soil moisture. The changes in NDVI are only valid if these represent accurately the changes in biomass, and so depend on the limitation of crop scanning, that is, are best for the rapid growth stages and when the canopy has not reached saturation of reflectance. Interpreting soil moisture changes as crop water use also needs to be examined carefully. Rain between surveys will obscure crop water use. The crop will have appeared to use less water for the growth over the survey interval. So only those intervals where rain was not present reflect the change in moisture due to crop use. If surveys are far apart the risk that rainfall will disrupted the sum of water use becomes more likely. These are not directly the fault of the survey methods but closer tracking of the moisture use by a crop might be needed. At the other end of the scale, frequent surveys with an EM38 trying to measure very small changes in soil moisture run the risk of being too small for real differences not to be obscured by instrument errors (around 3 mSm^{-1}). Careful calibration of the EMI instrument is also required to improve the confidence that changes in EC_a actually represent real soil moisture changes.

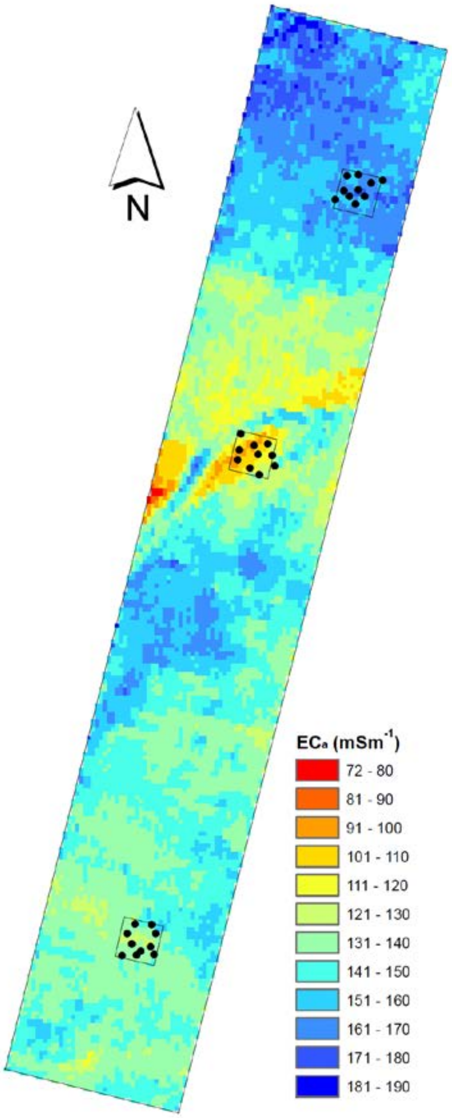
This survey provided confidence that where the quad-runner and sled could be employed regularly and with careful calibration of the EM38, both soil moisture and crop biomass could be surveyed and combined to give a measure of spatial WUE.

Stage 2: How well does ΔEC_a correlate to soil moisture content?

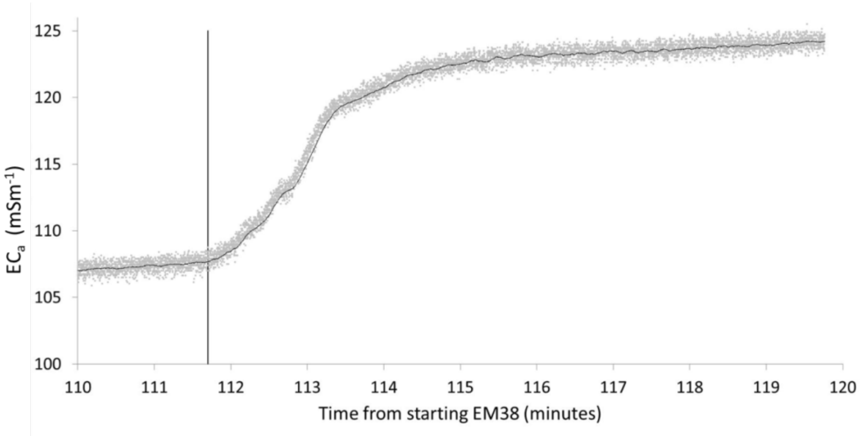
Photograph of the EM38MkII on variable height rack above neutron probe access tube, mid-season (January 2012) at Keytah (nr. Moree). The rack allowed the EM38 to be lower from 1.4 m in 20 cm increments down to soil surface level immediately beside each neutron probe access tube position.

Introduction

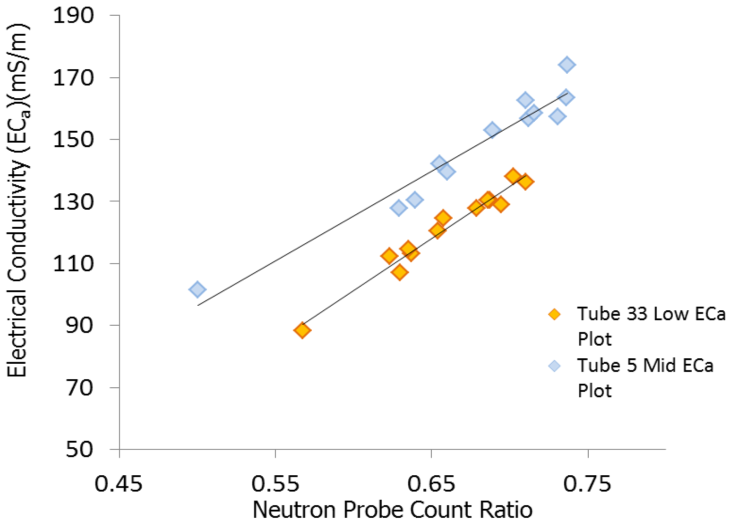
Experiments were conducted at Laureldale (Armidale) and Keytah (nr. Moree) to determine the strength of the relationship between changes in site-specific measures of soil conductance (EC), in our case EC_a (apparent electrical conductivity) and soil moisture content. Several previous studies allude to a good relationship but methods used by previous researchers did not isolate water as the exclusive influence on change (Kachanoski, 1988; Sheets & Hendrickx, 1995; Khakural 1998; Dang et al, 2011). We found that repeated measurements using a well-established standards (VMCs and neutron probe) and well calibrated EM38 returned very high correlations, founding confidence that soil moisture could be tracked under a crop using EMI surveys. The results of this experiment have been disseminated at national and international conferences. The details are presented in the attached papers (Appendix 1:A and 1:C) but highlights and some important diagrams have been reproduced here. A key aspect of this study was to use polyvinyl acetate neutron-probe access tubes so that the EMI survey device (EM38) could be used directly over the same volume of soil used to make the standard soil moisture measurement (using a neutron probe). This is something that previous studies had not done.



EMI survey of (W8) field at Keytah. Non-saline, heavy clay soils. 30 plastic (poly vinyl acetate) neutron probe access tubes sites are marked as black dots. Neutron probe and EM38 readings were taken at each site on 7 to 12 occasions over three months. The three square boxes mark a hectare of high, medium or low EC$_a$ for this field.



A single placement of and EM38 along the plant-line of a cotton row during an irrigation revealed a steady increase in soil conductivity as the soil wetted over about 3 minutes. This shows that for this particular position the soil had a background conductance at refill of ~107 mSm^{-1} and there was about a 20 mSm^{-1} range of conductance from refill to full point. This is the apparent electrical conductivity response that we are relating to soil moisture content.



The chart above shows two of the thirty neutron-probe sites. As neutron probe counts increase the EC_a increased linearly. Sites with a lower background EC_a, here probably due to a lower clay content show lower conductivity but retain the linear response. These look quite similar in slope but soil types are likely to vary considerably.

The conclusion of this experiment is that ΔEC_a of non-saline, heavy clay soils is a reliable indicator of soil moisture content for site-specific measures. Once an EMI survey has been conducted the background conductivity of each area traversed will be known. If that is done shortly after general rain then the full point for all sites will be known. After a second survey, ΔEC_a can be calculated for each site/zone and that will show a relative change in soil moisture content. Calibration against an absolute standard like volumetric soil moisture (VMC) will be needed if the actual soil moisture content is required. If the second survey is done when the soil has been dried down to wilting point, here at cotton harvest with no ensuing rain, the EC_a readings at this time will represent the lowest point of plant available water (PAW). Since the EC_a relationship to soil moisture content is a straight line, all future readings should fall on that line. The relationship is strong, ($r = 0.94$) for measures taken with a carefully calibrated the EM38, held 20 cm above the soil.

Limitations to tracking soil moisture under a crop emanate from instrument error and non-crop influences on soil moisture. A well calibrated instrument is needed, far fussier than general PA consultancies would want to do. Furthermore, over the course of a day or two the decline in EC_a under a crop would be small (~1 to3 mSm^{-1}). This is likely to be too small to distinguish amongst instrument calibration and general temperature corrections. Other difficulties are physical. The results of this experiment were achieved by placing the EM38 at each neutron-probe site within a cotton crop, not by carrying out a survey. For regular surveys to track crop moisture use, the crop must be conducive to regular trafficking, like a pasture. Note that regular passes across the same piece of ground with a quad-runner and sled would likely damage the plants that we are hoping will remain representative of the whole field. Such limitations point towards developing a farm vehicle mounted EMI survey device that can operate well above the crop in a similar fashion to the CropCircle™.

Using PA surveys of biomass and soil moisture maps to determine optimum in-season fertiliser rates for a commercial wheat crop at Jemalong Station.

Aim

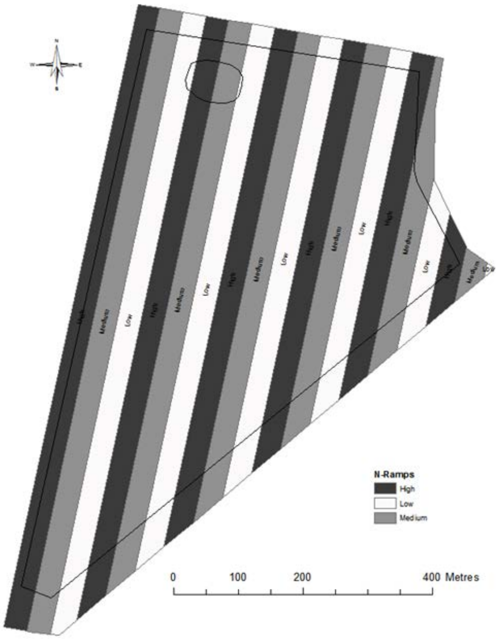
To determine the fertilizer requirements for variable-rate, in-season fertilizer based on a combination of biomass from crop scanning and soil moisture content from EMI surveys. Rather than attempt to apply fertilizer at different rates in response to soil moisture or crop biomass, the entire field was treated with a repeated ramp of fertilizer levels. This created all treatment combinations of fertilizer × EC_a zone × biomass zone which could then be interrogated for yield and quality (protein) responses. For example a high fertilizer strip would cross all possible water contents and biomass zones allowing us to see whether different fertilizer rates were optimum for different combinations biomass and Soil moisture zones.

Materials and Method:

Study site and data collection

A field of dryland (raingrown) dual-purpose wheat (*Triticum aestivum var.* Ventura) was selected at “Jemalong” Forbes, NSW (-33°27'5"S, 147°42'15"E). The crop was sown at a rate of 45 kg/ha on 30cm rows with an upfront application of 50 kg/ha DAP. Four calibrated EC_a surveys were performed, with a Geonics EM38 MK2 coupled to a dGPS receiver, at key stages; pre-crop fallow, sowing, flag leaf and harvest to get a good range of soil moisture levels.

Soil cores were taken during two of the surveys to calibrate EC_a to VMC. A total of 25 cores sites were selected based on 5 ΔEC_a zones derived by k-means clustering. VMC was measured on 10 cm core segments down to 80 cm and the 4 stationary EC_a measurements were taken by positioning the EM38 in different orientations centred directly over the VMC core hole. For the following analysis, the VMC’s for each of the 10 cm core segments were averaged for each site to give an average VMC and the EC_a values were also averaged.



Field of dual-purpose wheat (Dowra 7) paddock showing the N-ramp strips of fertilizer (0, 10 or 20 kg/Ha N) repeated across all EM and biomass zones. The boarder was clipped to remove edge effects.

NDVI and EC_a surveys were performed simultaneously using a quad-runner and sled to estimate biomass at the flag leaf growth stage and collect the initial EC_a reading for ΔEC_a calculation. At the same point 75 × 0.4 m^2 crop biomass cuts were taken to calibrate the NDVI to the green dry matter (GDM) of the crop. After this initial survey, foliar N fertiliser treatments (liquid urea, Ranger® at zero, 10 and 20 kg/ha) repeated as 36m wide strips across the field (**Error! Reference source not found.**). This does not apply fertiliser according to soil moisture content but covers all possible combinations of fertiliser rate × biomass × EC_a zone so that the potential benefits of site-specific treatment by fertiliser are revealed.

At harvest yield data was collected using the yield monitor on a John Deere 9660 STS header with Green Star 2 2600 display and integrated differentially-corrected GPS. Grain cuts were taken at harvest to calibrate the yield data to true tonnage and also to allow spatial interpolation of grain quality (protein content). Manual harvest sites were stratified randomly across ΔEC_a zones, (EC_a change from sowing to booting) and N-ramp locations. At each of the

150 manual harvest sites 4 replicates (1m^2) were taken within 4m of the GPS sampling position and averaged to give the yield estimate for that site. The grain cuts were threshed using a Hege plot harvester (stationary) before weighing and protein determination. A yield map from the previous year's canola crop was also available as a possible explanation of this year wheat yields.

Data processing and analysis

Spatial yield, EC_a and NDVI were rendered and processed using ESRI ArcGIS 10 and interpolated to a common 5m grid using Vesper (Minasny, 2003). The yield data was extracted using Field Operations Viewer, MapShots, 2009 running the Greenstar 2 Field Operations Device Driver and processed using Yield Editor 2.0.2 (USDA, 2013).

To compare the manual harvests to the header's yield monitor, a 6 m buffer of crop from the boundary of the field was removed. This avoids poorly registered values due to partial comb cuts by the header as it negotiates turns as well as variations in crop density caused by sowing along field boundaries. Secondary layers were derived from EC_a surveys to produce ΔEC_a and percent soil moisture. ΔEC_a is defined as the change in EC_a calculated between two stages, such as sowing and harvest. Percent soil moisture was calculated by finding the range of EC_a values at each location and determining the current survey EC_a on that range; i.e. at flag leaf stage the soil moisture at site x is 45% of the total range measured.

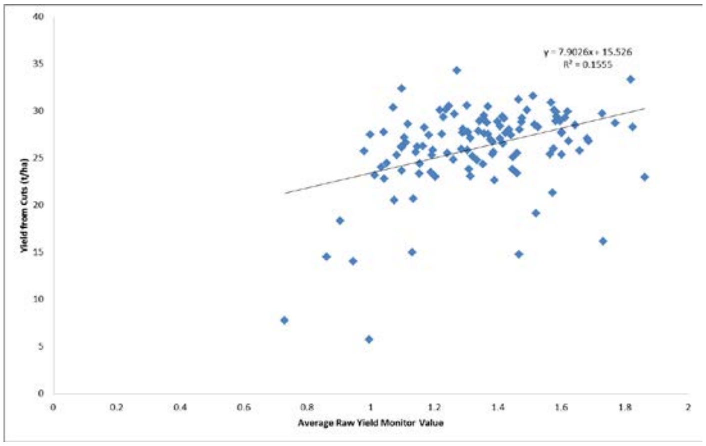
To assess the benefits of the N-application relative to the biomass and soil moisture content, NDVI and soil water percentage were clustered into 3 zones. These zones were joined to the N-ramps and the interpolated yield and protein results used to identify significant responses to the various fertiliser applications.

Results and Discussion.

Monitoring the wheat crop at Jemalong progressed well until the final series of measurements. The four EMI surveys successfully determined soil moisture content revealing a broad range of soil moisture availability (~23 to 50% at booting). Biomass surveys were also successful, correlation positively with soil moisture use but unfortunately in the final stages frost reduced the yield by approximately 50% nullifying the final yield measurements. Yield and quality (protein) mapping from the 150 manual yield and protein measurement sites (4 reps of each) revealed no difference across the field related to soil moisture, biomass nor fertiliser treatments. We did however demonstrate that the EMI survey was a good indicator of soil moisture content and that there was considerable variation in moisture across this 37 ha field. This suggests that for seasons where soil moisture was limiting, differences in fertilizer utilisation might be expected.

The yield measured at the 150 grain sample sites was normally distributed with a mean of 1.29t/ha and a standard deviation of 0.25t/ha. The average yield calculated from the interpolated yield monitor data was 1.35t/ha with a standard deviation of 0.07t/ha. A yield of 2.6 to 3.0 t/ha would normally be expected from this field given the good in-season rainfall (approx. 140mm) and favourable growing conditions despite sowing being delayed. It was very clear from the low proportion of ears producing seed that flowers had been destroyed by frost, ca. 6 to 10 ears survived from 20 to 30 ears per seed head.

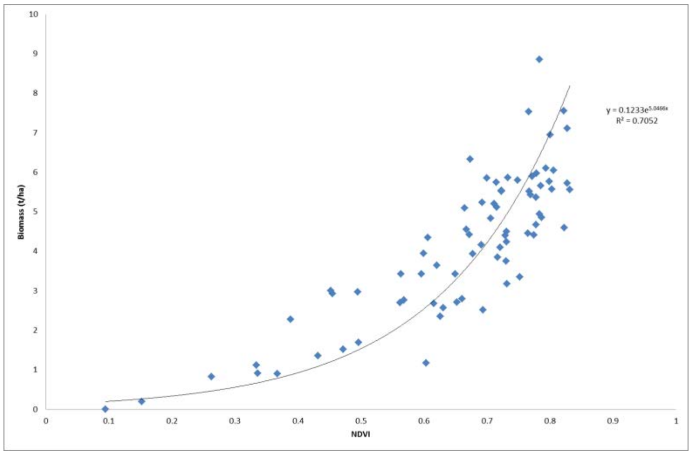
There was only a weak linear correlation (R^2=0.16) between the manual yield measurements and the harvester yield-monitor data. This is likely to be explained by the small manual sample (4m^2) revealing variability at a smaller scale than the harvester at ~33 m^2.



Calibration of the harvester's yield monitor to the absolute tonnage from manual sampling.

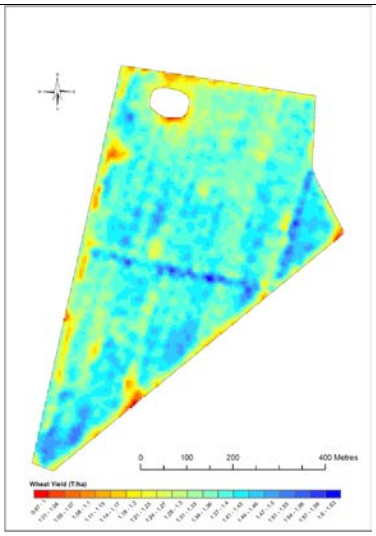
Biomass Calibration

At booting stage 75 × 0.4^2m crop cuts were taken to calibrate the CropCircle ACS-470 to green dry matter (GDM). The exponential correlation (R^2=0.71) was used to convert the raw NDVI to units of green dry matter (GDM). The majority of the crop was at the flagging stage though some areas were booting, which would account for a somewhat weaker calibration curve than usual.

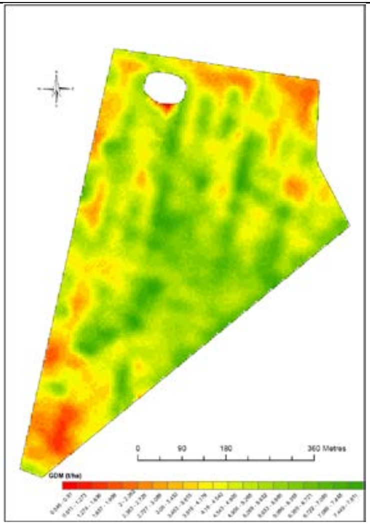


Exponential calibration used to convert of NDVI to green dry matter (GDM).

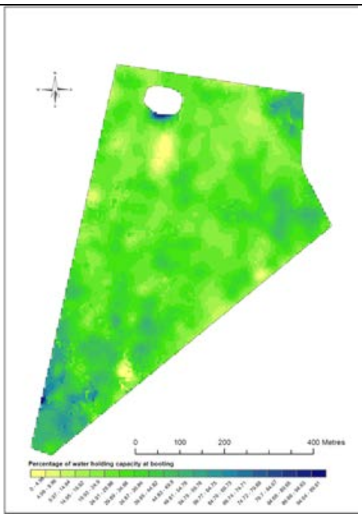
The correlations between all the primary and secondary interpolated data layers revealed that only ΔEC_a (from sowing to harvest) correlated to any extent with yield monitored by the harvester (R^2=0.14). ΔEC_a from sowing to booting however explained 34% of the variability in the biomass production measured by the crop scanner. Despite the disruption by the frost ΔEC_a remained the best way to assess the water used by the plants, both from sowing to booting and sowing to harvest. Least squares modelling shows that a combination of the layers (EC_a at sowing, booting water %, harvest water %, ΔEC_a at booting, ΔEC_a at harvest, GDM and the previous canola yield) cannot individually nor combined explain any more than 22% of the variability in yield ($R^2 = 0.22$). A combination of layers up to booting (EC_a at sowing, booting water %, ΔEC_a at booting and the previous canola yield) explained 40% of the variability in GDM at booting.



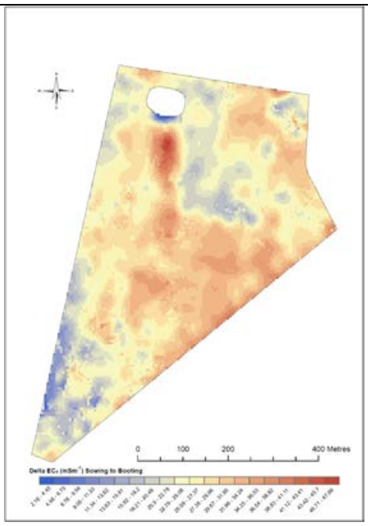
Wheat yield map



GDM map at booting stage



Percentage of soil moisture available at booting stage based on maximum and minimum EC_a values measured at different stages.



ΔEC_a map, higher values correspond to larger changes in EC_a.

Interpolated maps of wheat yield NDVI at booting percentage moisture at booting and ΔEC_a between sowing and booting are shown for general visualisation purposes.

K-means clustering was used to identify zones of High, Medium and Low soil moisture percentage at booting and High, Medium and Low GDM levels at booting. The cluster means and standard deviations for soil moisture percentage and GDM are shown in **Error! Reference source not found.** and **Error! Reference source not found.** respectively.

Means and standard deviations for moisture percentages at booting

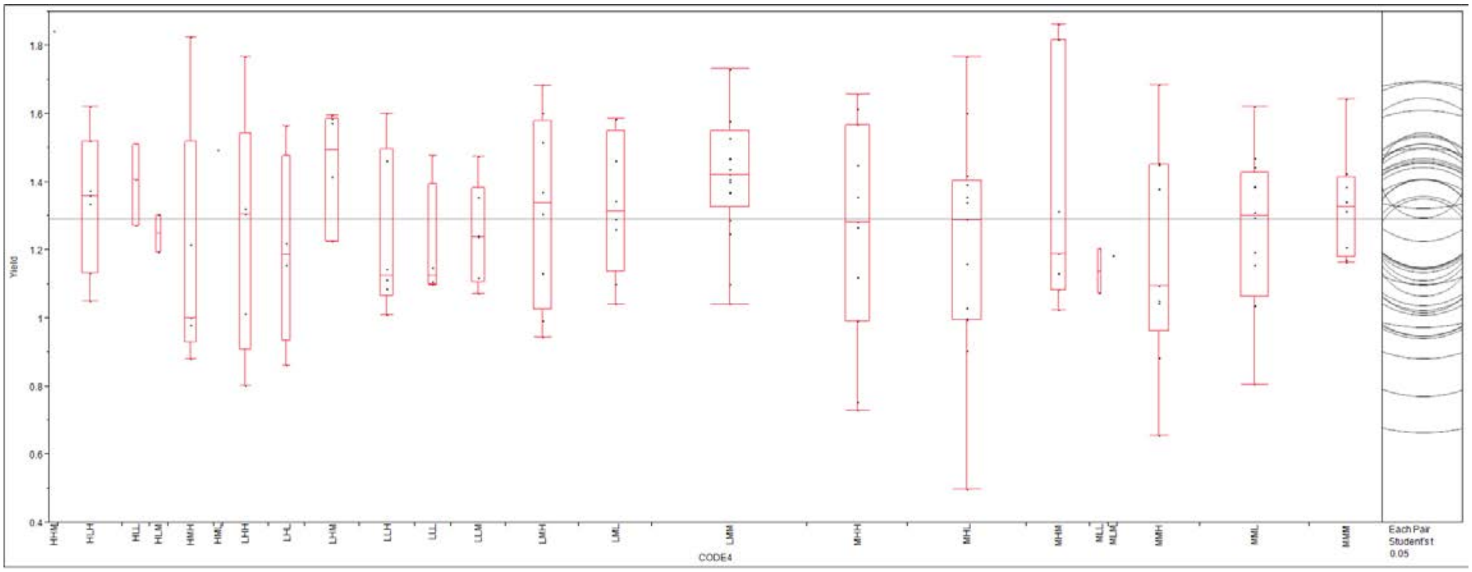
Zone	**Mean**	**Standard Deviation**
High Moisture %	50.48	7.28
Medium Moisture %	33.48	3.70
Low Moisture %	22.78	5.00

Means and standard deviations for NDVI at booting

Zone	**Mean**	**Standard Deviation**
High GDM	6.19	0.493
Medium GDM	4.85	0.409
Low GDM	3.34	0.620

There was no significant difference ($p>0.05$, AOV) between the yield of high to low GDM, High to low moisture content (indicated by the VMC) nor between the high, medium or low nitrogen rates. This is considered to be due to the levelling effect of the frost damage which removed approximately 70% of the flowers-seeds.

Analysis to determine whether any combinations of moisture zone, GDM zone and nitrogen-rate had a significant effect on yield. There was no significant difference across all treatments.



Analysis showing no differences in yield from all possible combinations of moisture %, GDM and N-rate, coded in that order (H,M,L).

Conclusions from fertilizer experiment on wheat at Jemalong:

Unfortunately the fundamental aim of this experiment was seriously compromised by the frost damage. Any possible relationship between the spatial measurements of moisture, biomass and fertilizer level explaining the distribution of yield was removed by the frost. However, the ΔEC_a was found to show the best relationship with biomass so in a year where soil moisture was the yield-limiting factor, perhaps the maps of soil moisture would have been a useful to guide fertilizer additions, but this remains unconfirmed.

On a practical level, the surveys were possible that related biomass to soil moisture content. This validates the methods at a research level but concern was expressed about the potential damage cause by the tramlines though the crop (see CRCSI partner responses on page 42). Managing to collect the EMI surveys and crop scans without pulling a sled would be preferred. If the EM38™ could be mounted on a spray rig it would be held well above the crop and record subsequent surveys from unaffected plants. The EM38 readings correlated to moisture content from over a metre above the crop but the relationship reduces to r = 0.80 (Appendix 1:A). This was not tested, to avoid risking the current expensive devices.

Overall Conclusions from this Activity.

Biomass measurement using active optical sensors like the CropCircle™.

Scans using active optical sensors consistently provided a good relative indication of the crop biomass during this activity. Current methods for scanning from ground-based vehicles (eg. quad-runner or 4WD) as typically done by PA consultants provided reasonable correlations with biomass over the intermediate growth stages of the crop. The interpretation of biomass from these surveys for use in water use efficiency calculations is reasonable as long as the limitations of this method are understood.

Limitations in interpretation of biomass scans as an accurate and precise indication of actual crop biomass and/or yield.

1) As the crop matures at harvest the amount of chlorophyll declines rapidly and sufficiently unevenly to be highly misleading about current biomass and eventual yield.
2) Maximum reached NDVI does not always indicate yield for many crops.
3) A high NDVI is a combination of crop quality and crop leaf density. So a low NDVI can be few very healthy plants or many poor plants.
4) Biomass might not correlate to economic yield, so the relationship between quality (in this case grain protein) needs to be understood.

Limitations to the practical methods of using crop scanners.

1) Generating tram tracks using a small vehicle has the potential to damage the crop directly and so can only be used infrequently and at less vulnerable stages of crop growth. This has two impacts on the acceptability of these methods for maps of WUE. 1) direct damage will deter adoption of this method by growers unless it is obvious that losses are more than compensated for by the increased productivity. At this stage the improvements to productivity are uncertain. Secondly, the damage means that the follow-up surveys for Δbiomass and ΔEC_a are compromised by plants that might not be representative of the general field. Both our commercial partners (Bryan Goldsmith of the Twynam Group, and Nick Gillingham of Sundown Pastoral Company) expressed concerns about the inaccessibility of their crops for quad-runner based surveys and perceived problems with the damage caused by repeated surveys.

Soil moisture measurement using EMI soil survey sensors like the Geonics EM38™.

Site-specific ΔEC_a consistently provided a good relative indication of soil moisture content for the soil beneath a crop for non-saline, heavy clay soils. This was evident from the repeated stationary positioning of the EM38 to VMW correlations at the UNE farm, Laureldale and the correlations between the neutron probe and EM38 at Keytah (Sundown Pastoral) and during all calibrations between VMC and ΔEC_a along- side the field surveys at Keytah and Jemalong (Twynam Group). This provided considerable confidence that the difference in EC_a (ΔEC_a) from general EMI soil surveys could be interpreted as soil moisture as long as particular attention was paid to calibration of the instrument and the circumstances of the crop between surveys. In order to interpret the soil moisture levels as crop water use, that is, if we intend to link the biomass and soil moisture surveys to produce a map of WUE, then surveys need to be frequent enough to capture all soil moisture changes, especially inputs of rain. This is unlikely to occur unless rain is infrequent. Assumptions are made simple if there has not been any rain and it will be on these occasions that WUE will usually be revealed. Another route for water loss that should not be seen as crop water use is drainage. Drainage from the root-zone would be registered by the ΔEC_a survey but the importance of this would depend on whether losses here form part of the WUE efficiency question.

It remains a scientific fact that a single EC_a reading, as done here for each position along a survey transect, cannot distinguish between a large amount of conductance (higher amounts of soil moisture) at greater depth from lesser moisture (probably less salt) closer to the surface. For example, a reading of 160 mSm^{-1} at a site changing to a reading of 140 mSm^{-1} for the next survey (i.e. a ΔECa of $20mSm^{-1}$) can mean a general decline in soil moisture across a metre depth of root-zone or moisture draining from the top to the bottom of the root-zone, with perhaps no real loss of plant available moisture. A three dimensional view of soils for moisture at certain depths could be gained by multiple EC_a surveys using different sized EMI survey devices or instruments that collect several depths in a single pass. Furthermore, the measure of ΔEC_a remains largely a relative measure. Calibration curves can be generated by physically taking volumetric soil moisture cores across a site and producing a calibration curve. This follows the usual methods of correlating variable to spatial surveys, for example for converting ECa maps into salinity or soil texture maps (Triantifilis et al., 2000; Trantifilis and Leech, 2005). However, this averages the calibration, simply giving the moisture contents a realistic figure, rather than providing detailed moisture calibrations for each site-specific ΔEC_a relationship. The greater resolution provided by the surveys, albeit a relative measure may be preferable to absolute measures of soil moisture.

Limitations in the interpretation of EMI surveys as an accurate and precise indication of soil moisture use by crops.

1) Considerable calibration would be required to generate actual soil moisture contents from the relative measures gained via EMI surveys. This would mean taking soil cores for VMC across the field of interest and correlating certain depths of soil moisture content to various EMI instrument depth responses. Note however that even as a relative measure ΔEC_a from full point to refill reflects crop extraction, and therefore represents plant available moisture (PAW) for that crop type and over that growing season. This could well identify water availability problems as demonstrated by Dang et al. (2011) where constraints due to chloride at depth were identified in cropping similar heavy clay soils. They, likewise, used EMI measurements as an indicator of soil moisture content. Several years of EMI surveys would likely provide situations where ΔEC_a represented the maximum and minimum moisture contents.
2) Temperature did not become a major influence on EC_a in our trials but must be considered for crops that grow across large changes in soil temperature. General temperature corrections have been published by Huth et al. 2008?, and these might be very useful in these circumstances.
3) Day to day changes in soil conductivity (ECa) are unlikely to reflect real changes in soil moisture. Extraction of moisture by a crop is likely to be too small from day to day to become apparent above the noise (errors) of the instrument and calibration uncertainty. So large intervals of a week or greater are more likely to be a better indication of changes to soil moisture.
4) The accuracy of attempts to use relative soil moisture measurements in actual or even relative calculations of WUE need to be heavily qualified. Since there are errors with the accuracy of the biomass correlation, and the soil moisture measure, and these differ

considerably depending on the timing (crop stage and soil temperature), survey interval duration (shorter produces larger errors), influence of other limitations, only the most fortuitous circumstances will reveal WUE. As with our attempts to demonstrate the generation of WUE maps, rain between surveys or frost damage can easily derail the common sense reasoning that is required. However, the only way to gain spatial information about root-zone soil moisture at potentially important resolutions of 10 to 100 m sq at this stage is with EMI surveys. A large number of such surveys would inevitably produce the data set showing a) how commonly believable WUE arise and b) how broadly applicable to the industry or nation such measures are. This is why a cheap EMI technology that avoids the PA consultants methods would be so useful at getting to the truth about moisture distribution and productivity.

Limitations to the practical methods of using EMI soil survey instruments as they are currently available.

1) The same practical problems exist for EMI surveys as for crop scanners. Generating tram tracks through a crop using a quad-runner-like vehicle has the potential to a) damage the crop directly and so can only be done infrequently and at less vulnerable stages of crop growth. The absolute area of damage is very small but the perception by growers is much larger. And, b) crop damage along the transects means that subsequent surveys are collecting data from soils affected by unrepresentative plants. This puts a question-mark of unknown extent over the validity of the delta biomass records. Both our commercial partners (Bryan Goldsmith, Twynam Group, and Nick Gillingham, Sundown Pastoral) made comments about the inaccesability of their crops for quad-runner based surveys and particularly their agronomists perceived problems with the damage caused by repeated surveys.

2) The current barriers to using these surveys are; a) somewhat scientifically technical; we need to develop EMI instruments that focus on measuring soil moisture at root-zone depths; b) econometrically technical; current devises are targeted towards a small market of researchers and consultants leading to high costs per instrument and for use;

and c) agriculturally technical; we need to find ways to get the instrument over the soil without disrupting the crop.

Possible solutions to these limitations.

1) An EMI device that could be carried much higher above the crop could avoid the crop damage, especially if it was monitoring the crop beneath a spray rig or similarly sized vehicle. Surveys could be done whenever other operations were carried out. Many surveys would fall when the deltaECa was not of much relevance but if the equipment was cheap enough and the data could be computed quickly and cheaply then the potential benefits to cost ratio would become much more favourable.
2) As airbourne crop sensing becomes more viable, perhaps from drones, the biomass side might become very quick and inexpensive. A soil moisture map in conjunction with this would be helpful.

Feedback from CRCSI Partners

Paraphrased from **Bryan Goldsmith** (Twynam Group)

30 km South-West of Forbes NSW. Dryland/raingrown wheat and canola cropping plus cattle production.

Mapping soil moisture appears instantly appealing to broad acre, dryland cropping but once you have the map, it is not obvious how you would use it. We would sow even if the field was quite dry, hoping that in-season rain would produce a viable crop. So pre-season preparation would not be altered by obtaining a high-resolution moisture map, for us even if it was highly accurate. Perhaps the first in-crop nitrogen application could be altered by knowledge that various zones of the field were wetter or drier than others. We might give wetter and higher biomass areas more fertiliser.

On a more positive note, if I knew the crop was well supplied with moisture as it got towards harvest I would be in a better position to sell earlier with greater confidence. This would not have helped this year with the frost however. I am concerned about traversing the crop to do multiple surveys, no-one likes their crop to have tramlines though it, so it would need to be obviously an economic benefit. At the moment it looks like it might influence the position I take on the risk involved with certain decisions but is not directly prescriptive for management.

Paraphrased from **Nick Gillingham** (Sundown Pastoral)

30 km west of Moree NSW. Irrigated cotton enterprise with wheat rotations plus several other crops including chick peas etc.

Given that the project has shown it is possible to measure relative soil moisture content via EMI surveys, how might you use these in your enterprise?

I must admit that we are becoming inundated with data layers from precision agriculture surveys, like yield, elevation and crop biomass. Given the cost and time to deliver the information we are at the point where, if it doesn't provide clear and instant advise on a fix we don't really want to use it. At the moment, field elevation surveys dominate our use of PA for the direct benefits of improving irrigation distribution and uniformity. EM surveys have been used here to indicate soil texture but additional surveys for spatial water maps are unlikely to show us more than I believe we already know from the farms network of C-probes and rainfall gauges. So, if you are saying that repeated EMI surveys can tell me the potential bucket size across individual field; I believe I already know that well enough from several years of yield maps and experience using push probes. Options to respond to spatial water content are limited. We do not have the capacity to irrigate according to the zones the EMI may show. Realistically, we have to irrigate our surface-furrow areas on a field × field basis because we have to keep filling supply channels and head ditches. Refilling head ditches to irrigate a particular section of field at a different time to the rest would be too difficult. I can see that more regular EM surveys might identify areas I am currently unaware of but after farming the fields for many years, I don't expect we are too far from the optimum.

However, we often rely on pre-sowing moisture for wheat crops, so perhaps we would add N-fertiliser, up-front to a crop based on the levels of moisture at sowing, shown by a moisture map.

How to use ΔEC_a to generate maps of soil moisture content and relate it to crop growth

Two Views; Immediate or General Potential.

Maps of ΔEC_a can be viewed as a real-time indication of soil moisture content for a site or an indication of general site potential. The first brings up visions of a fertiliser rig fitted with a spectral sensor and an EMI survey instrument. The spectral sensor inputs current crop biomass and the EMI sensor registers the current EC_a. The biomass is interpreted via computer as the current crop amount (density) × quality, or uses previous surveys of biomass to determine Δbiomass for growth rate, likewise the EC_a can be interpreted as a ΔEC_a from previous surveys to indicate the amount of soil moisture at each site. Fertiliser is added based on the crops biomass and vigour along with the available moisture to support further growth. Poor growth would encourage greater fertiliser (as currently the practice in the USA) but this would be tempered by the soils store of moisture, i.e. more moisture would encourage more fertiliser. This implies the ideal, on-the-go decision and variable-rate application of this idea. A step back from this would be to map both previous to the fertilizer application, and then develop prescription maps, perhaps even incorporating other layers to improve the 'site-specific potential' given recent surveys.

The second approach we are calling 'spatial soil-moisture potential' relates to identifying the better areas or zones based on several years of ΔEC_a and biomass mapping. Several wheat crops could present a pattern of areas that hold and release more water, more PAW, ie. more potential and should in general be given higher priority, provided with more fertiliser and suitable seed and sowing rates. For any specific type of crop, several years of measuring ΔEC_a could provide 'bucket-size' for each site or zone in a field. The bucket size might be limited by soil type, structure, salt content etc. The response to this information could be to fix the compaction, sodicity, drainage, or add nutrients. Yield mapping might already be showing such areas, but the combination of biomass and ΔEC_a could help to diagnose soil type and moisture issues.

Relative versus Absolute measurements of soil moisture for agriculture.

It is worth adding a note on the measurement of soil moisture in agriculture because it is often intuitive to expect that measurements of soil moisture need to be calibrated to accurate soil moisture in order to be useful. Virtually all soil moisture probes measure via indirect relationships to soil water content whether that be via the neutron probe registering changes to hydrogen ion concentrations (in general) or capacitance probes using changes to the dielectric permittivity (K_a) of the soil. Calibration to absolute soil moisture requires sampling, usually drawing cores that are then cut up into sections and weighed, first wet then after oven drying, to determine weigh loss which is a direct measure of soil moisture in the sample. Despite neutron and capacitance probe support software delivering displays in units of mm of water for growers to become accustomed too, most are used without comprehensive field by field calibration and rarely is that necessary for broad-acre irrigation management. As long as the grower becomes familiar with the readings from a probe and the levels of moisture in relative terms that require response, the units become immaterial. Of course, if farms are to be compared on an absolute basis, calibrations are required, but this will involve a great deal of cost and effort to gain volumetric soil moisture measurements in conjunction with whichever probe is used. Even then the calibration would only place a realistic nominal figure on the data. True calibration at the scale of the EMI survey would calibrate for each site, and that is virtually impossible. I raise these points to qualify expectations of EMI surveys to provide useful information to farmers about soil moisture content. It is possible that several years of regular EMI surveys would reveal useful information about soil moisture changes without extensive calibration.

Final Comment

This project has attempted to measure spatial WUE, a goal that in theory would enhance our capacity to identify cropping practices that increase productivity and possibly supply an immediate measure of biomass and soil moisture content that could direct immediate decisions affecting fertilizer efficiency. We have managed to increase confidence in the mapping of soil moisture content with EMI surveys but been unable to generate confident WUE maps from the two PA survey methods. The crops we worked with were generally not limited by water availability. However, the goal of gaining higher resolution measures of WUE remains a valid one. The biomass reading is OK, the ΔEC_a is accurate but it doesn't always relate to a meaningful question about WUE.

Frequent surveys, perhaps weekly or before and after-rain, would be necessary to log each interval of soil moisture change to infer crop water use. The correlations between ΔEC_a with soil moisture content will be more accurate over larger (longer) changes in soil water content, small changes in EC_a of only a few mSm^{-1}, (a couple of days of crop use) will be influenced by instrument calibration errors of a similar order. Notwithstanding the problems that are often likely to interfere with a direct interpretation of PA survey collected ΔEC_a / biomass as WUE, enough farmers gaining maps of ΔEC_a on a regular basis would surely produce many data sets where WUE was informative.

This activity has greatly increased the confidence that ΔEC_a can be mapped at high resolution on heavy clay soils but highlighted the problems of expense and potential crop damage in the current methods for doing so. Attention to the development of an inexpensive, purpose-built EMI survey instrument that could be mounted on a spray rig to regularly collect EM surveys would be necessary to fulfil the potential raised by this research.

Acknowledgments

The authors acknowledge the support of our CRCSI commercial partners, Nick Gillingham of the Sundown Pastoral Company and Bryan Goldsmith of the Twynam Group for access to their properties and cooperation with the field experiments of this activity. Note however that specific mention of the names of commercial providers or products (eg Geonics EM38™, or Holland Scientific CropCircle™) does not constitute an endorsement of that particular provider or product.

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Triantifilis J, Lesch SM (2005) Mapping clay content variation using electromagnetic induction techniques. *Computers and Electronics in Agriculture* **46**, 203-237.

Appendix

Journal Articles:

Appendix 1:A

John N. Stanley, David W. Lamb, Gregory Falzon and Derek A. Schneider. 2014. Apparent electrical conductivity (EC_a) as a surrogate for neutron probe counts to measure soil moisture content in heavy clay soils (Vertosols). *Soil Research* (accepted Jan 2014) CSIRO.

Appendix 1:B

J.N. Stanley, S.E. Irvine, D.W. Lamb and D.A. Schneider. 2013. Effect of Aluminum Neutron Probe Access Tubes on the Apparent Electrical Conductivity Recorded by an Electromagnetic Soil Survey Sensor. *Geoscience and Remote Sensing Letters, IEEE.* 11 (1) 333-336. DOI: 10.1109/LGRS.2013.2257673.

Conference Proceedings:

Appendix 1:C

John N. Stanley, Derek A. Schneider and David W. Lamb. 2012. Site-specific measurements of apparent electrical conductivity (EC_a) correlate to neutron moisture probe counts: Towards the spatial measurement of soil moisture content for precision agriculture. *Proceedings of the 16th Australian Agronomy Conference.* 14th – 18th October 2012. Armidale, NSW, University of New England.

Appendix 1:D

J.N. Stanley, D.A. Schneider, and D.W. Lamb. 2012. Spatial apparent electrical conductivity (ECa), soil moisture and water use efficiency in Vertosol soils. Proceedings of the 12th International Conference on Precision Agriculture. 15th – 18th July 2012. Indianapolas, Indiana. USA.

APPENDIX 1:A

Apparent electrical conductivity (EC_a) as a surrogate for neutron probe counts to measure soil moisture content in heavy clay soils (Vertosols).

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Running heading: EC_a to neutron probe correlations

Abstract

Site-specific measurements of the apparent electrical conductivity (EC_a) of soil using the EM38 (Geonics Ltd. Canada) were correlated with near-simultaneous neutron probe readings over periods of moisture extraction by an irrigated cotton crop. Thirty sites were monitored from three EC_a zones within a 96 ha field of grey Vertosol soil 30km west of Moree, New South Wales, Australia. This study differs from previous approaches by reporting the effect on EC_a of a wetting front (irrigation) reaching a single EC_a measurement point in a field and by using polyethylene neutron probe access tubes so that the EM38 could be operated directly over the same site measured by a neutron probe. We report strong correlations (r = 0.94) between neutron probe counts (CRR) averaged to a depth of 40 or 60 cm and EC_a from an EM38 held in the vertical mode 20cm above the soil surface. All combinations of EM sensor height (0 to 1.2m) to neutron probe measurement depth (0.2 to 1.4m) returned correlations greater than 0.85. The relationship between CCR and EC_a was linear for the purposes of estimating water content over a range of background EC_a levels. More critical modelling suggested a slight curve (logarithmic model) fitted best. The range of surface surveyed EC_a from the start of irrigation (refill point) to fully irrigated (full point) was around 27 mSm^{-1} for this vertosol, where surface EC_a readings typically ranged from 50 to 200 mSm^{-1}. We suggest that the calibration of EC_a to CRR might be effected by a two-point measurement of the soil, namely at both upper (field capacity) and lower (wilting point) EC_a values, and a site-specific calibration template generated by extending these point measures to whole field surveys.

Key Words

ΔEC_a, spatial water use, electromagnetic induction survey, precision agriculture.

Introduction

Along with soil salinity and texture, soil moisture content has long been recognised as a major component of apparent electrical conductivity (EC_a) as measured at the soil surface by electromagnetic induction (EMI) instruments (Kachanoski *et al.* 1988; Khakural *et al.* 1998; Huth and Poulton 2007; Hossain *et al.* 2010). Salinity or texture often dominate the EC_a response to such an extent that a single electromagnetic induction (EMI) survey, with appropriate ground validation, can provide high resolution maps of these variables (eg. Triantafilis *et al.* 2000; Triantafilis and Lesch 2005). However, the less dominant and more frequently changing contribution made by soil moisture is often obscured.

A typical EMI soil survey instrument, like the EM38 (Geonics Ltd. Ontario, Canada), returns a single figure that represents the total EC_a of the soil within the sensing range (approx. 1.5 m depth when operated in the vertical dipole mode) integrating all factors that contribute to soil EC, i.e. salinity, clay, moisture, porosity, organic matter and cation exchange capacity etc. and all interactions. The reading commonly ranges from 50 to 200 mSm^{-1} across non-saline, heavy clay soils such as the grey Vertosol (self-mulching, haplic) in this study (Dang *et al.* 2011, Isabell 2002). The aim of our study was to isolate the contribution made by soil moisture to the EC_a reading by repeatedly returning to precisely the same sites in a field over an extended period of time and to correlate the instrument response to the widely used neutron soil moisture probe (Greacen 1981).

Over a relatively short time period, a few growing seasons, two of the main factors that influence soil EC_a, namely clay content (texture) and salinity, for any given point in a field are essentially fixed (see review by Sudduth *et al.* 2001). Therefore, repeated measures of EC_a at fixed sites over a relatively short period could be expected to reflect, almost exclusively, those changes caused by changes to soil moisture content. The presence of highly saline zones or the addition of saline water via irrigation are however highly influential and were avoided in our study by choosing a field of low soil EC and where high quality irrigation water was available. Such soils represent the majority of the irrigated cropping areas of the mid-western wheat belt extending from central Queensland to southern New South Wales.

Several other factors influence soil EC_a including CEC, bulk density and porosity but these are again essentially fixed for a site (Sudduth *et al.* 2001). Fluctuations in temperature, as ambient influences on the instrument or by changes to the EC (increasing salts in solution) of the soil via soil temperatures, are the only variables, beyond water content, expected to influence EC_a significantly during the time frame of our experiment (Padhi and Misra 2011). Discussion on likely influence of temperature is presented along with the results of this experiment.

Measuring the same site repeatedly using the EMI method and a reliable standard is not easy. The usual approaches are compromised. Either; a) the standard measure interferes with the EC_a meter when used at exactly the same site, one after the other; neutron probes using aluminium access tubes have this problem; or, b) the standard method disturbs the site forcing future measures to be taken from a different position, thereby failing to isolate water as the only influence in a correlation; using soil cores for volumetric moisture content (VMC) as the standard measure suffer from this problem.

In this paper we present correlations between site-specific measurements of an EM38 and a neutron moisture probe but using polyethylene access tubes so that the two instruments can be used at the same time and same location (Stanley *et al.* 2012). Note that absolutely simultaneous readings of EC_a and another meter are virtually impossible because the electrical operation and/or metal components of the standard probe will likely influence the EMI device. The few minutes (max. 5 min) between measurements with each device used here is not considered important because soil moisture extraction by a crop is insignificantly small over such a short period.

Materials and Methods

Three, one-hectare square plots were marked out across a 96 ha field of grey Vertosol soil planted to cotton at 'Keytah' (ca. 40 km west of Moree, NSW Australia, Latitude: 29°29'43.23"S Longitude: 149°34'5.31"E). The plots provided a convenient way of generating a range of sites of different background EC_a identified from a previous field-wide

EMI survey (low = 80 to 120; mid = 120 to 145 and high = 160 to185 mSm^{-1}) (Figure 1). Ten polyethylene access tubes (56 mm outer dia. x 3.3 mm wall thickness x 1.8 m long) were inserted into the plant row at randomly selected locations in October 2011, three weeks after sowing. All tubes were inserted to 1.5 m depth, cut off at 20 cm above the soil surface and capped. The field had 1.5 m wide beds, i.e. plant rows were 0.75 m apart with an irrigation furrow between every second row. Furrow run-lengths were 400 m requiring approximately 4 hours under syphon-fed, surface-furrow irrigation to complete. EC_a and neutron probe readings were taken at each access tube over a three month period that included four irrigations and several rainfall events. Readings were taken with the EM38 (Geonics Ltd. Ontario, Canada) in the vertical mode positioned 0, 20, 40,....140 cm above the soil surface in line with the plant row and up against the centre (non-irrigated furrow) side of the access tube. Sixteen-second counts were taken at 20, 40…140 cm depths using a neutron moisture probe (Hydroprobe® Boart Longyear, Model 503DR, California, USA). Both instruments were used at each access tube on nine to thirteen occasions across: January (16,18,20,22); February(16,19,20,22,24); March (2,12,13,14,15); and April (9,10) in 2012. Standard neutron probe counts were made in a large water barrel on a monthly basis and all access tubes used to determine standard counts were identical to those used in the field experiment.

Additionally, on the 17 February, EM38 readings were logged for 18 hours (time zero was 1:45 am AEST) while an irrigation of the field was in progress. On that occasion the EM38 was housed in a plastic box, placed on a 1 cm thick strip of rubber matting in the vertical mode and oriented along the centre of the non-irrigated furrow between two irrigated furrows approximately 50 metres into the field from the head ditch. The aim was to record the EC_a as water infiltrated the soil beneath the EM38 for the time required to raise the water content from refill point (water content when irrigations are initiated) to field capacity. This would indicate the magnitude of the change in EC_a that represents the change in soil moisture for these heavy clay soils over moisture contents relevant to irrigated cropping.

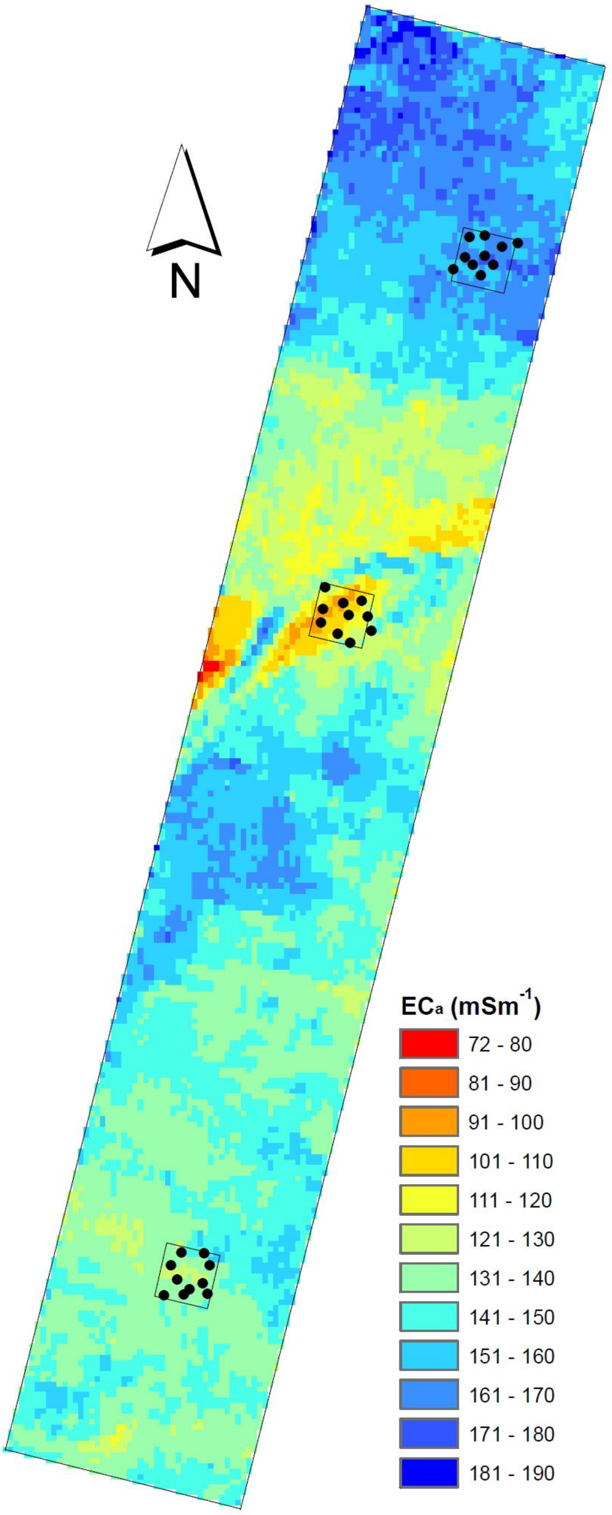

Figure 1. Initial EMI survey using EM38 in the vertical mode for the field planned for irrigated cotton (2.4 × 0.4 km). Shows the three, one-hectare square plots of high, medium and low EC_a levels that generated the range of background EC_a levels for the neutron probe access tube installations indicated by (•)

During three irrigation events samples of the water from the head ditch were collected to determine electrical conductivity (EC_e). Three 500 ml samples were taken from the centre of the head-ditch channel by reaching down from a foot bridge midway along the head ditch and submerging each opened bottle to 10 cm below the surface of the water. The general soil EC and bulk density profile of the soil in this field was determined by extracting ten soil cores and using $EC_{1:5}$ (Slavich and Petterson 1993) and measuring with an ECTestrs11 meter (Eutech Instruments Pty Ltd). For bulk density, typical volume to mass measurements were determined by drying 10 cm long x 38 mm dia. soil cores at 110ºC and correcting for shrinkage using the methods of Yule (1984).

Data analysis: All analyses were conducted using R data management software (R Development Core Team). Neutron probe counts are expressed as ratios of field counts to standard water barrel counts to give the count rate ratio (CRR). Pearson's correlation was used to describe the relationship between EC_a and CRR for each tube-site. The response surface in Figure 4 of EC_a to CRR correlations for the full range of combination of EM38 height to neutron probe depth was produced with multi-level, B-spline approximations using package 'MBA' with four levels (Finley and Banerjee 2010). A linear, mixed-effects model (command 'nlme and allowing for separate intercepts and slopes) identified the statistically significant trend of EC_a with log10 (corrected CRR) conditioned with respect to each tube (Pinheiro et al. 2013).

Results

The electrical conductivity (EC_e) of the irrigation water collected on three occasions (12th Jan, 17th Feb, & 15th Mar 2012) while irrigations were in progress returned an average EC_e of 25.2, 27.4 and 26.9 mSm^{-1} (SD 0.21, 0.61 and 0.15 mSm^{-1}, respectively at 25ºC, n=3). The average bulk density of the soil in the field was 1.37 t soil/m^3 at 0.2 m and increased marginally to 1.48 t/m^3 at 1 m (average SD = 0.14, n= 10). The $EC_{1:5}$ of the soil was 7.5 mSm^{-1} (SD = 1.36 n = 5) for the 0 to 0.25 m depth interval and increasing to 33.5 mSm^{-1} at 0.75 to 1.0 m (SD = 16.3 n = 5).

Soil EC_a increased markedly in response to the irrigation wetting front. Figure 2 shows a 27 mSm^{-1} increase (105 to 132) as the soil wetted, mostly over a period of about 3 to 10 minutes but settling after 12 hours to 127 mSm^{-1}. Figure 3 displays the region of rapid rise in EC_a in more detail.

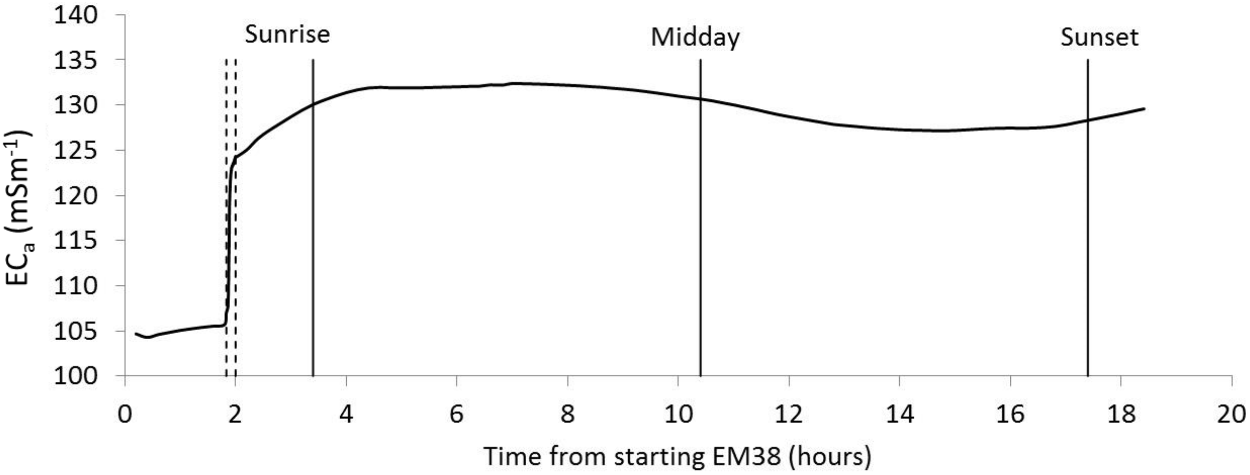

Figure 2. EC_a records from a stationary EM38 run for 18 hours in the vertical mode during a surface-furrow irrigation event. The trace reports the EC_a readings collected at a rate of 13.9 per second. Instrument error (SD = 0.4 to 0.6 mSm^{-1}) was removed for graphing by plotting the average for every 1000 samples (equivalent to an average every 1.2 minutes). To capture the rapid rise in EC_a the section from 1hr 50 mins to 2 hr was averaged for every 100 points (i.e. equivalent to an average every

7.2 seconds). The vertical dotted lines indicate the region magnified in Figure 3.

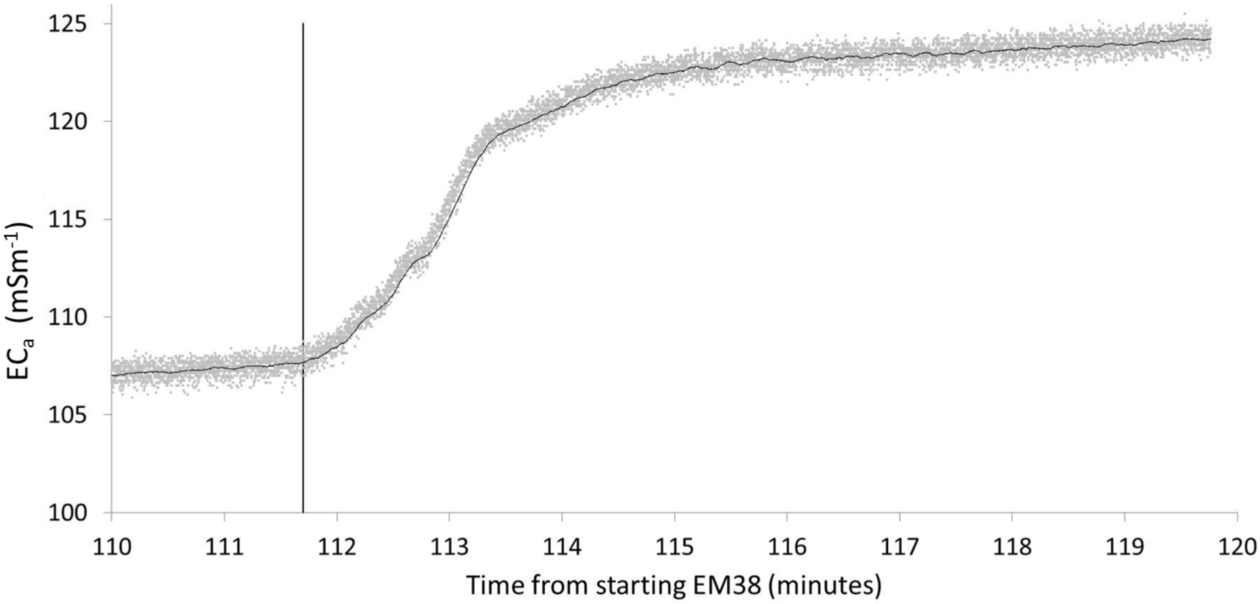

Figure 3. EC_a records over the 10 minute period when irrigation water was infiltrating the soil beneath the EM38. The grey points are actual EC_a readings (13.9 per second) illustrating the range of instrument error. The fine black trace is the moving average for every 100 data points. The vertical line indicates the estimated arrival of the wetting front.

The clear increase in soil EC_a to wetting (Figures 2 & 3) was consistent with correlations of EC_a with CRR (Figure 4). The best correlations of EC_a readings to CRR occurred when the EM38 was held at 20 cm above the soil surface and the CRR was averaged to a depth of 40 or 60 cm (Figure 4). All combinations of EM38 sensor height to 1.2 m and integrated CRR to a depth of 1.4 m produced correlations greater than 0.85 (Figure 4). Statistical analysis of the linear mixed-effects model indicated a strongly significant relationship between EC_a and CRR with respect to tube-site ($t = 23.53930$, $p < 2.2e-16$). Figure 5 presents the linear relationships for each of the 30 sites for EM38 height of 20 cm and CRR records to a depth of 40 cm.

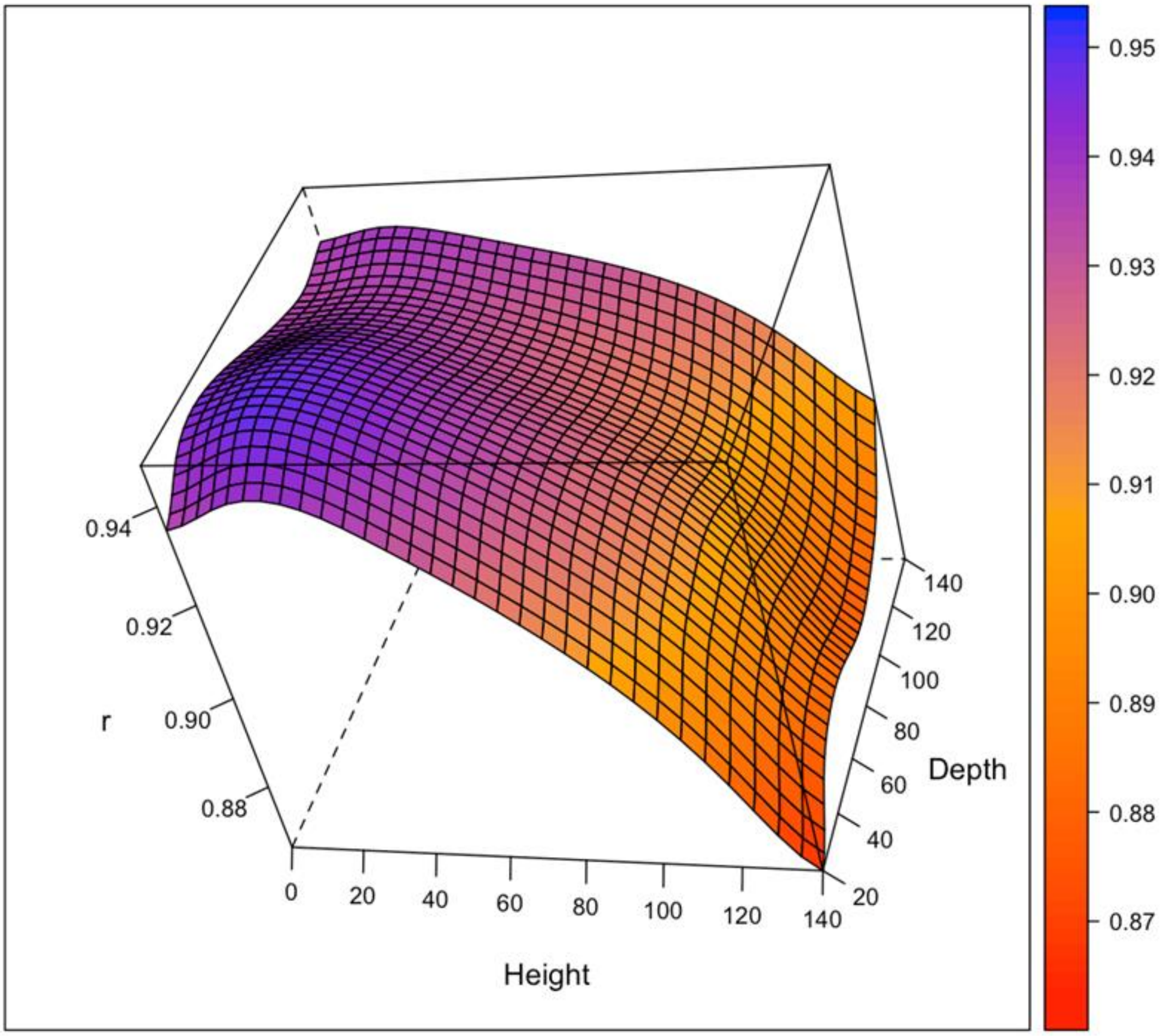

Figure 4. A three-dimensional surface (multi-level B spline) representing the Pearson's correlations of EC_a to CRR for each combination of EM38 sensor height (Height) and neutron probe depth (Depth) for all access tube-sites.

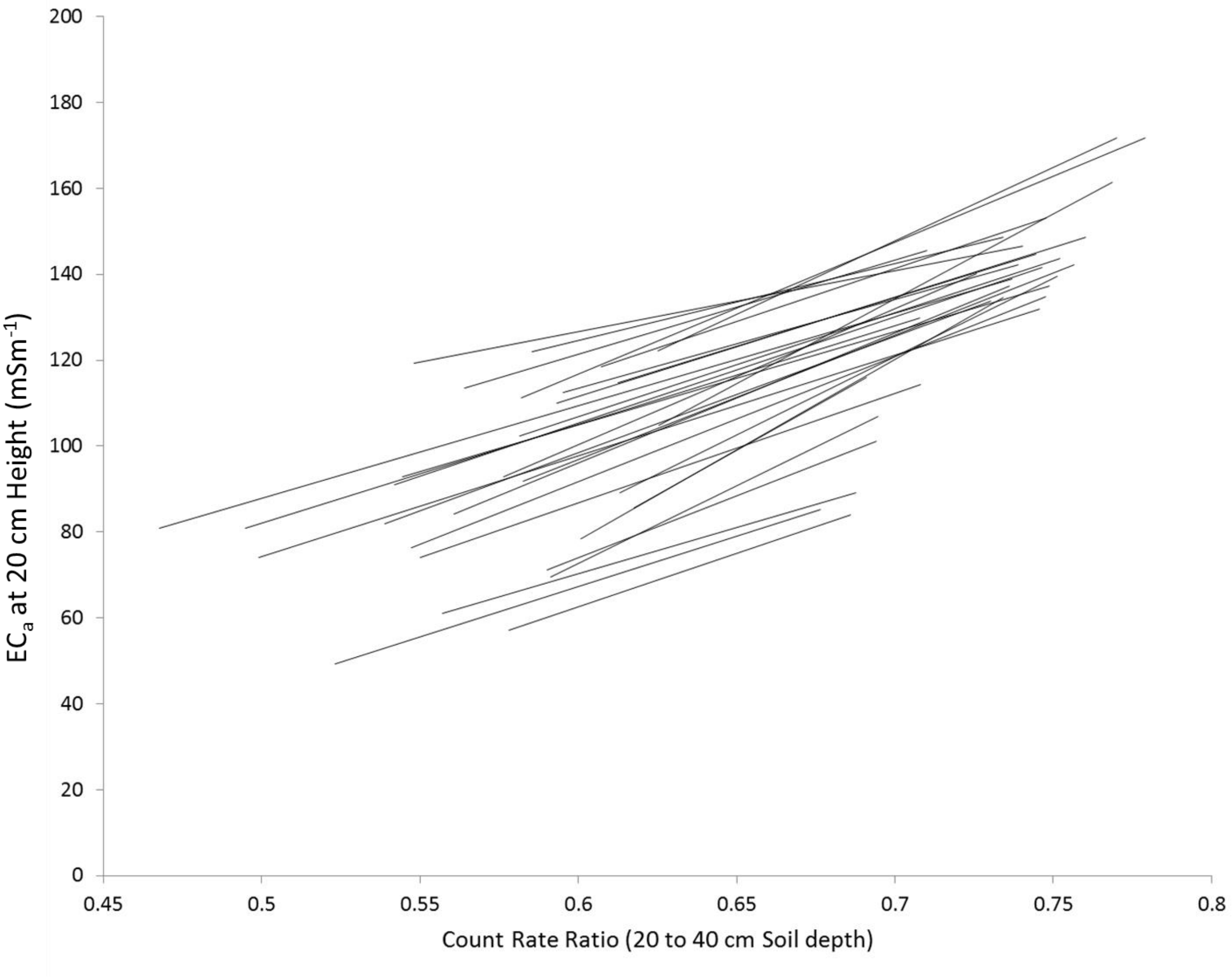

Figure 5. Linear relationships between EC_a and CRR for the thirty individual access tube sites for EM38 sensor height 20cm and CRR to 40cm depth.

Discussion

This study has firstly demonstrated the magnitude of the immediate EC_a response to infiltration from refill to full point for a Vertosol soil typical of many broad-acre cropping regions of Australia. In this case the EC_a was shown to increase by about 27 mSm^{-1} over a period of only ten minutes during irrigation. Secondly, we have isolated the influence of soil moisture content on the change in EC_a for any given site in a field by methods that allowed us to repeatedly sample the same site using the EM38 and an established standard for nondestructive soil moisture measurement, the neutron probe. The strong linear correlations (r = 0.84 to 0.94) between these two gauges for a range of EMI sensor positions and soil depth ranges suggest that surveys to determine site-specific EC_a could be interpreted as soil moisture content. Preliminary surveys would be required to establish the site-specific EC_a for a dry soil status of interest, i.e. wilting or refill point and also a wet end of the spectrum, i.e. full point. Because of the proportional relationship, future high resolution EM maps showing the current site-specific EC_a, with reference to known dry and wet EC_a levels, would reveal the current soil moisture content for each site.

When the EM38 was left in the field to record EC_a during an irrigation event there was a small increase of about 1 mSm^{-1} over the two hours prior to the wetting front reaching the sensor (Figure 2). This incremental rise could be attributed to changes in ambient temperature or instrument drift. Sudduth *et al.* (2001) demonstrated changes of up to 3 mSm^{-1} per h for repeated EC_a measurements along a fixed transect but emphasised that the reasons for drift could not be explained by readily obtained measurements like ambient temperature. Losses of water from the soil via transpiration or evaporation would be minimal during this time of night (i.e. 1:45 to 3:35 AEST). Significant drainage or other redistributions which might also alter the soil moisture content in the vicinity of the EM sensor would also be unlikely over such a short period and at this later end of the irrigation cycle. However, this small experiment was not designed to interrogate those finer aspects. What was demonstrated was a definitive and regular sigmoidal increase of about 27 mSm^{-1} in soil EC_a as the water infiltrated the soil beneath the sensor (Figure 2 & 3). Highly saline irrigation water might also have explained this but the water was measured to be only 25 to 26 mSm^{-1}. The marked effect on EC_a, was almost entirely related to the influence of water filling the soil profile which therefore suggests that EC_a could be a useful surrogate for soil moisture content.

The cracking nature of these vertosol soils would explain the early rapid infiltration rate. Water would readily fill cracks and infiltrate pore spaces beneath the instrument on many fronts, rather than the slow, one-dimensional infiltration downwards, expected of non-cracking clays (Smiles 1984). The EC_a continued to increase over the following two to three hours but then settled by 5 mSm^{-1} to 127 mSm^{-1} after 12 hours. This is consistent with EC_a reflecting overall root zone moisture content because, under surface-furrow irrigation, the soil would be expected to saturate, at least near the surface, and then decline towards its drained upper limit (field capacity) as the water redistributed across and down through the soil profile during the hours following irrigation (Smiles 1984). The decline in EC_a observed when daily temperatures were increasing, or rising EC_a as ambient temperatures decreased after sunset, is due to the lag between air and soil temperature within the measurement range of the EM38, and is consistent with correction factors published by Huth and Poulton (2007). Two battery changes for the EM38 occurred, one at 6:30 am and the other at 12:15 pm (AEST). No change in EC_a was observed across either change. This simple exercise has identified a magnitude of EC_a response (approximately 27 mSm^{-1}) to soil wetting.

The site-specific correlations between EM38 and neutron probes counts reaffirmed the potential usefulness of the response of EC_a to soil moisture. The better correlations corresponded to the shallower neutron probe readings and lower EM38 instrument heights while sensing (Figure 4). This is to be expected because the cotton crop was mainly removing moisture from 0 to 60 cm (evident from a commercial capacitance probe installation) and the EM38 is most sensitive to changes in conductivity from 20 to 60 cm away from the instrument (McNeill 1992). Furthermore, lifting the EM38 to 20 cm above the soil surface serves to align the most sensitive region of the EM38 response curve with the layers of soil where moisture was most variable (Morris 2009). Since the change in EC_a in this configuration explained greater than 90% of the variation in CRR, this provides strong evidence that, for these soils and over a reasonably short time frame, EC_a could be used as a surrogate for soil moisture. Sheets and Hendrickx (1995) successfully fitted linear regressions to soil moisture content along a 1.95 km transect using an EM31 and 65 neutron probe sites for calibration over a 16 month period.

EMI sensors and neutron probes operate on very different fundamental principles, so there does not appear to be a direct, mechanistic explanation for their good correlation. Neutron probes register the number of hydrogen ions in the vicinity of the neutron emitter and counter. Although there are many sources of hydrogen in the soil the only readily changing source almost certain to be water, hence, changes in CRR correlate to changes in water content for any given point-location (Greacen 1981). EMI soil sensors register the EC_a of the soil, a function not about hydrogen ion content but of; the abundance of electrolytes (salt content), abundance of ion-loaded surfaces (clay content) and abundance channels through which currents might flow. All of which appear to interact with water to increase conductivity (Sudduth et al. 2001). With both instruments the isolation of water content is only effected by registering changes that occur for a given site because other influences, matric hydrogen ion or clay content remain static for most practical purposes.

The good correlations in the absence of corrections for temperature suggest that a useful indication might be possible without parallel temperature measurements. Sudduth *et al.* (2001) was able to make considerable improvements to EC_a correlations with topsoil depth by simply grouping measurements on whether they were collected when it was ‘hot’ or ‘cold’. For measurements taken across a few months, as for this experiment, the effect of temperature on EC_a appears to be of little consequence. Note however that the three months of our experiment correspond to a relatively stable period of daily temperatures. Improvements by including temperatures corrections have been published by Huth and Poulton (2007). From

January to March at Moree when the majority of the measurements were taken for this experiment, they estimate the correction factor required would range from 0.91 to 0.93, a difference of only 2%. By April, our final measurement date the correction factor will have reached 1.02 and by the coolest month of August at Moree, a factor of 1.27 is required. Huth and Poulton (2007) provide these corrections as a general seasonal influence in agroforestry systems. Immediate changes to temperature caused by the infiltration of cool irrigation water were not explored however the strong relationships demonstrated in our study would suggest that immediate temperature changes are not particularly important for estimating general soil moisture content for crop management purposes.

For many situations in broad acre cropping EMI surveys could provide high resolution maps of EC_a rapidly. The strong linear correlations described in this paper auger well for interpreting such surveys as moisture maps. Strategically timed EMI surveys would be needed to identify the range of EC_a for each site. That is, one when the field is essentially at field capacity, shortly after heavy rain or irrigation, and one when the moisture is severely depleted following dry-down by a successful crop. These two surveys could identify the limits of field capacity and wilting point for each site or zone in a field for a particular crop. The linear response of EC_a to moisture content would then be applied to future EMI surveys to identify the current moisture content at each site. Likewise, the difference between any two EC_a maps of the same field taken at different times (with considerations of the influence of temperature) would produce a ΔEC_a map potentially showing changes in moisture content that might identify zones for differential crop management

The resolution of such surveys, i.e. how many sites or zones that would be needed, would depend on the economic benefits of knowing this information and the ability to variably manage specific sites for fertiliser, irrigation, or seeding rate etc. For some purposes it may be sufficient to establish the full point and use a common slope equation for moisture draw down per EC_a unit since the slopes exhibited in Figure 5 for a wide range of EC_a appear broadly similar. Note, however that there are differences in the slope between sites so application of this approach would depend on the required accuracy of the estimation. Since current farming practices in broad-acre agriculture do not measure soil moisture content beyond very low resolution rainfall/climate information or at best from only a few soil sensors for every hundred hectares (eg. irrigated cotton production), using EM surveys would represent a major step towards monitoring plant available soil moisture spatially.

Acknowledgments

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Appendix 1:B

The effect of aluminium neutron probe access tubes on the apparent electrical conductivity recorded by an electromagnetic soil survey sensor

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Abstract

Efforts to correlate soil moisture content to apparent electrical conductivity (σ_a), as derived from above-ground, electromagnetic induction (EMI) dipole sensors, often use physical probe moisture meters such as capacitance or neutron probes as a standard. To this end, plastic or metallic access tubes (ca. 0.5 to 2m long, 40 to 50 mm internal diameter and 1 to 2mm thickness walls) are inserted vertically into the soil to allow the probe to be lowered for moisture readings at a series of soil depths. Little is known about the impact of these tubes on measurements derived from above-ground electromagnetic induction (EMI) sensors when the sensor is in proximity or adjacent to these buried tubes. This technical note reports on the impact of widely-used aluminium (Al), as well as popular 'plastic' alternatives of polyethylene (PE), polyvinylchloride (PVC) access tubes on the lateral σ_a profiles of an EM38 EMI meter as it is moved along survey transects that pass beside the access tubes. There was no significant difference observed between the EMI meter readings of the bare soil and the vertical holes created to house the access tubes nor when the plastic access tubes were in place. However the Al tubes showed a considerable variation in readings once the EM38 meter was within 50 cm of the tube location. A theoretical model, based on a single dipole transmitter and receiver coil, and a thin cylindrical shell beneath the earth's surface confirmed the horizontal eddy currents, travelling around the tube shell to be responsible for the observed deviation in the senor response when in proximity to the metallic tube.

Introduction

Active electromagnetic induction (EMI) soil sensors were originally developed for geophysical prospecting and detecting buried ordinance. In recent years their use has expanded to include measuring agriculturally-relevant soil attributes without the need for disturbing the soil. Typical devices used in agriculture comprise of co-linear transmitting and receiving induction coils with an inter-coil spacing of the order of metres. The single value of apparent electrical conductivity, σ_a (the nomenclature eC_a is sometimes used), returned by the sensor at any given location on top of the soil is an integrated value based on a combination of the depth-related sensitivity of the instrument and the depth-dependent drivers of electrical conductivity (e.g. moisture content, salinity etc.) (McNeill, 1980; Sudduth et al., 2001; Hossain et al., 2010). It has proven possible to generate site-specific calibrations between the σ_a returned by the instrument and actual soil parameters of interest including moisture content (Hossain et al., 2010), clay content (Williams and Hoey, 1987) and salinity (Slavich and Peterson, 1990). Soil moisture is a significant factor in interpreting spatial variations in σ_a (Sudduth et al., 2001; Brevik and Fenton, 2002), notwithstanding the fact that it is an essential parameter in its own right in terms of crop and pasture management. Consequently the deployment of active EMI instruments will often be in conjunction with other in-situ soil moisture measuring technologies, many of which are physically inserted into the soil and involve electrically-conducting components. Capacitance (Dean et al., 1987) and neutron scattering probes (Bell, 1969) are widely used in-situ devices to measure soil moisture, although other techniques such as gamma ray transmission (Ryhiner and Pankow, 1969) have also been tested. Each of these techniques involve the placement of vertically oriented access tubes into the soil. In the case of neutron probes, aluminium tubes are used because they are transparent to neutrons, whilst capacitance probes generally utilise polymer tubes of zero conductance. The tubes are typically several centimetres in diameter, tens of centimetres in length, and have wall thicknesses of the order of a few millimetres. Any active EMI soil sensing device used in close proximity to these tubes may respond to their presence and it would be expected that any soil σ_a survey be designed so as to avoid potentially confounding influences of these tubes on acquired data. Certainly numerous researchers have used access tube-based instruments in support of EMI investigations of agricultural soils (for example Kachanoski et al., 1990; Sheets and Hendrickx, 1995) although in all cases the access tube locations were positioned far from the sensor transects (here of the orders of metres) to minimise any undesired influence of the conducting access tubes on the sensor readings. To the best of our knowledge a systematic investigation of the nature of the EMI response to such access tubes has not been performed, especially with the goal of providing informed suggestions on deployment conditions aimed at eliminating spurious signals. Moreover, the recent development of theoretical models for investigating the response of EMI sensors to buried conductors (McKenna and McKenna, 2010; Irvine, 2012) also provides an opportunity to understand the physical mechanism of sensor response to metallic access tubes. This paper describes an investigation, supported by theoretical considerations, into the effects of metallic and non-metallic access tubes on the response of an EMI soil survey sensor widely used in agricultural science.

Theory

In order to model the response of a generic soil sensor to a conductive access tube, a simple and intuitive model has been developed and is similar to one developed previously (Irvine, 2012). The geometry of the problem is illustrated in Figure 1. Ultimately, the goal is to spatially traverse an area of soil and map the electromagnetic response using the sensor. As shown in Figure 1, the device may be located next to an access tube, which will undoubtedly provide a response. To first order, the tube, being a thin cylindrical metallic shell, can be considered to be a static dipole located at some effective distance below the surface of the Earth. The sensor itself is assumed to contain a single dipole transmitter (Tx) and a single dipole receiver (Rx), separated by a fixed distance. The sensor is assumed to travel in a straight line, which lies above the dipole and is offset horizontally. As described previously

(Irvine, 2012), the overall response of the sensor would be a function of the response of the transmitter as well as receiver. The overall response can be derived by simply considering the magnetic field due to the dipole representing the cylinder, and the dot product of this field with the dipole moments of the transmitter and receiver of the sensor at their respective spatial locations. Experimentally, slight deviations from the ideal situation depicted in Figure 1 have been incorporated in the model and include small changes in the polar and azimuthal angles of the Tx and Rx, as well as a rotation of the device about an axis perpendicular to the transect path, represented as β in Figure 1.

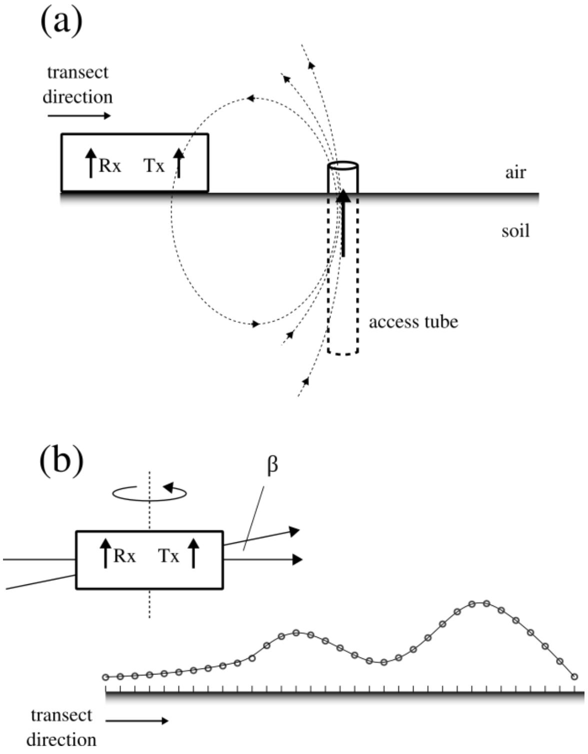

Figure 1. (a) Geometrical representation of a soil conductivity sensor traversing over the Earth. Here, the sensor is comprised of a single transmitter dipole (Tx) and a single receiver dipole (Rx). Also shown is a metallic access tube that lies adjacent to the survey transect of the sensor. (b) Illustration of the method of the experimental data acquisition. The sensor was stepped along a predefined path. At each position of the path, the sensor location and apparent conductivity was calculated. Also shown in the inset is the tilt parameter (in-plane with the air-soil interface), β, which takes into account a slight misalignment of the long axis sensor. It should be noted that the orientations of Tx and Rx could include deviations in their polar or azimuthal angles, which are not illustrated.

Materials and Methods

The trial site was located 2 km north of the University of New England campus (Armidale, NSW, Australia) in a field of heavy clay soil (vertosol) sown to ryegrass pasture and recently grazed to an average height of 30 mm above the soil surface. A single, 10 m long, linear transect was surveyed and marked on the field using spray paint and a plastic measuring tape placed along the line (Figure 2). The midpoint of the transect (x = 500 cm) was marked for vertical insertion of the various access tubes. Step-wise measurements of above-ground apparent electrical conductivity (σ_a; mS/m) were conducted at 10 cm intervals from x = 0 – 400 cm, followed by 2 cm increments from x = 400 – 700 cm, and then 10 cm increments from x = 700 – 1000 m, using an EM38 induction sensor (Geonics, Ontario, Canada). This sensor comprises vertically oriented dipoles, one a transmitter and one a receiver, which are separated by 1.0 m. The sensor was nulled according to standard protocol (McNeill, 1980) and then moved along the transect with its transmitter-receiver coil axis aligned along the transect to mimic the conditions of a typical 'tow-along' survey (Lamb et al. 2008). The σ_a values were recorded using a Geoscout (Holland Scientific®) data logger. Three types of access tube were evaluated: polyethylene (PE), polyvinylchloride (PVC) and aluminium (Al). All tubes were 50 mm diameter and inserted to 85cm soil depth with 20 cm protruding from the soil surface. Series of σ_a recordings were made along the transects in the following order: 1) undisturbed ground (control); 2) ground plus empty access tube hole created by the soil coring machine; 3) ground plus aluminium tube, 4) ground plus PVC tube, and 5) ground plus PE tube. Each time a σ_a reading was collected, the operator stepped back at least half a metre from the device (Figure 2).

Drift of the EM38 was observed to cause a small (ca. 1 to 2 mS/m) increase across the whole experiment. Corrections for drift were made by calculating the average difference between each survey point in a profile from the same position in the undisturbed ground profile (control profile), and then subtracting this from all points in the profile.

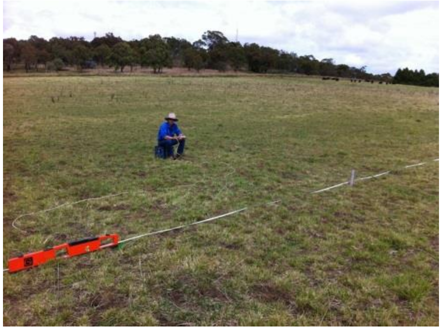

Figure 2. Layout of the measurement transect showing alignment of the EM38 sensor along the 10 m transect and the aluminium (Al) access tube in place.

Results and Discussion

Figure 3 displays the five σ_a profiles for the five treatments.

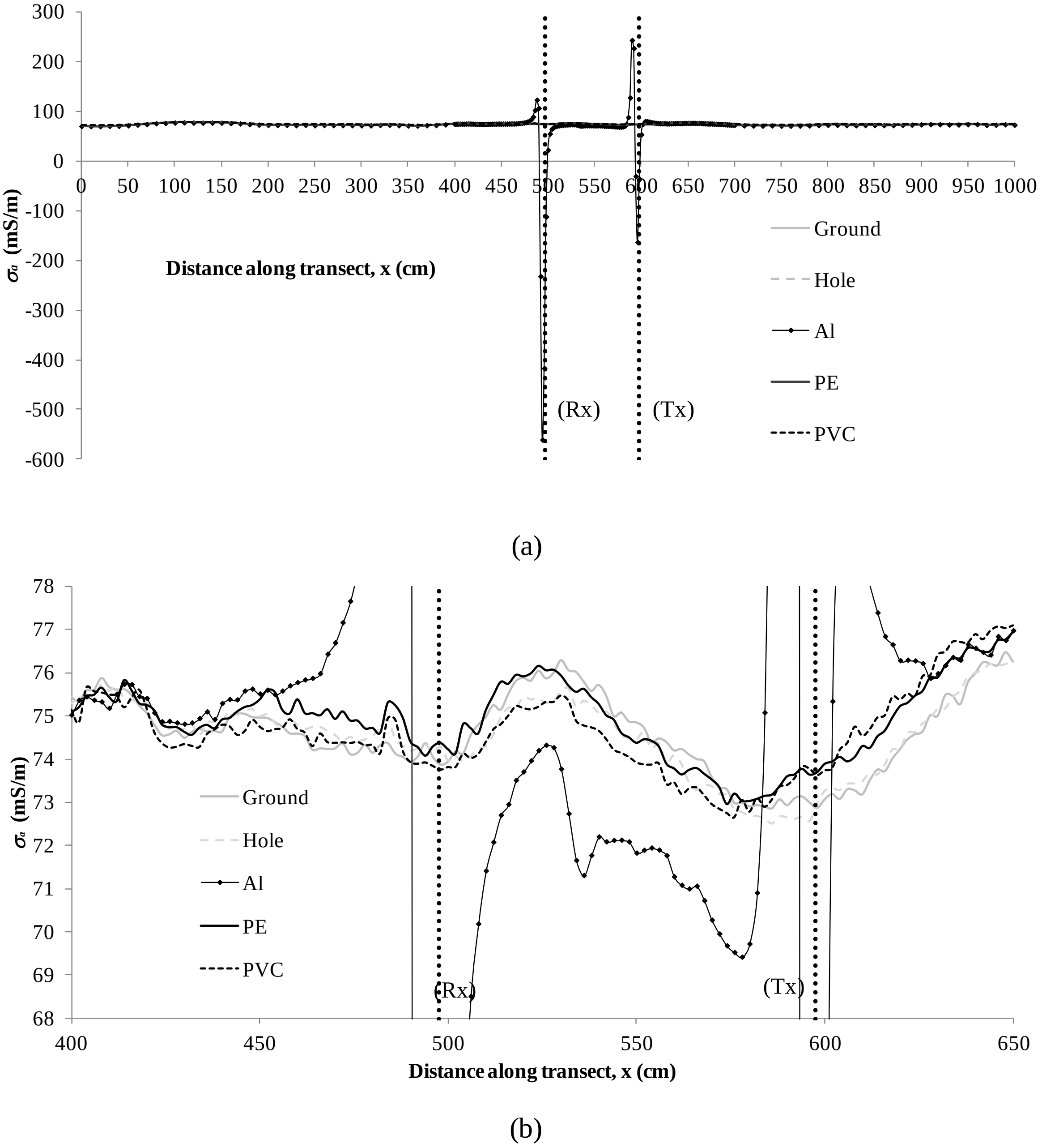

Figure 3. σ_a profiles for the five treatments showing (a) full transect and full scale of σ_a range, and (b) a subset of the transect data showing a magnified σ_a scale adjacent to the access tube location (x = 500 cm). The dotted vertical lines indicate the access tube position when the leading EM38 receiver coil is adjacent (Rx) and when the following transmission coil is adjacent (Tx).

Neither the initial ‘clean’ hole created by the soil coring device (Hole), nor PE or PVC access tubes caused any significant difference in σ_a profiles compared to the undisturbed ground (Ground). Any small deviations do not suggest any systematic effect, rather are likely the result of instrument drift and possible sensor-ground height variations induced by the grass (Brevik et al., 2003; Sudduth et al., 2001; Morris, 2009). The presence of the electrically-conducting Al tubes causes a large perturbation to σ_a relative to undisturbed ground when either of the transmitter or receiver coil of the EM38 is within 50 cm of the access tube.

Interestingly, when the sensor has straddled the access tube location, where the coils are approximately 50 cm either side of the aluminium tube, the σ_a reading is only a few mS/m from the undisturbed soil reading. This has also been observed when using the EM38 in the vicinity of tall, steel, vineyard trellis posts (Lamb et al., 2005).

Figure 4 depicts the sensor response and that predicted by the theoretical model. The model calculations confirm that the EMI instrument comprising co-planar, vertical dipole, transmit and receive coils (in this case the EM38) to be influenced by the vertical, conductive access tubes when within ca. 50 cm from the tubes (ca. half the inter-coil spacing within the sensor). As it was not possible to determine the transmitter power, the theoretical results are normalised in relative units. The agreement between the theoretical and actual sensor response to the conductive access tubes suggests sensor response to these access tubes to be dominated by horizontal eddy current travelling around the circumference of the tubes; a key assumption in the model. The process of implementing the model showed the magnitude of the sensor response when placed in close proximity to the conductive access tube to be highly sensitive to small variations, of the order of only a few degrees, in the alignment of the transmit and receive coils. These alignment parameters, as stated in the discussion of the theoretical model, include the orientation of the transmit and receive dipole axes as well as the horizontal alignment (β) of the transmit - receive coil axis. While every effort was made to ensure alignment of the sensor relative to the cylindrical axis of the access tubes during each survey, such small variations were inevitable. Such variations are evident in the experimental data presented in Figure 4. In order to obtain the match between the experiment and theory, small tilt angles of up to 5 deg were used for the polar and azimuthal angles of the Tx and Rx dipoles, as well as the dipole representing the access tube. Moreover, the in-plane tilt angle, represented by β, was set to a mere 0.3 deg in order to achieve agreement. Evidently, the shape of the profile is very sensitive to this parameter. The dependence of the profile on minute changes in this parameter can be understood geometrically. That is, a small change of β will lead not only to a change of position of the Tx and Rx (given their separation of 1.0 m), but is also changes their orientations with respect to the access tube dipole. Clearly, both of these effects contribute to changes in the signal profile.

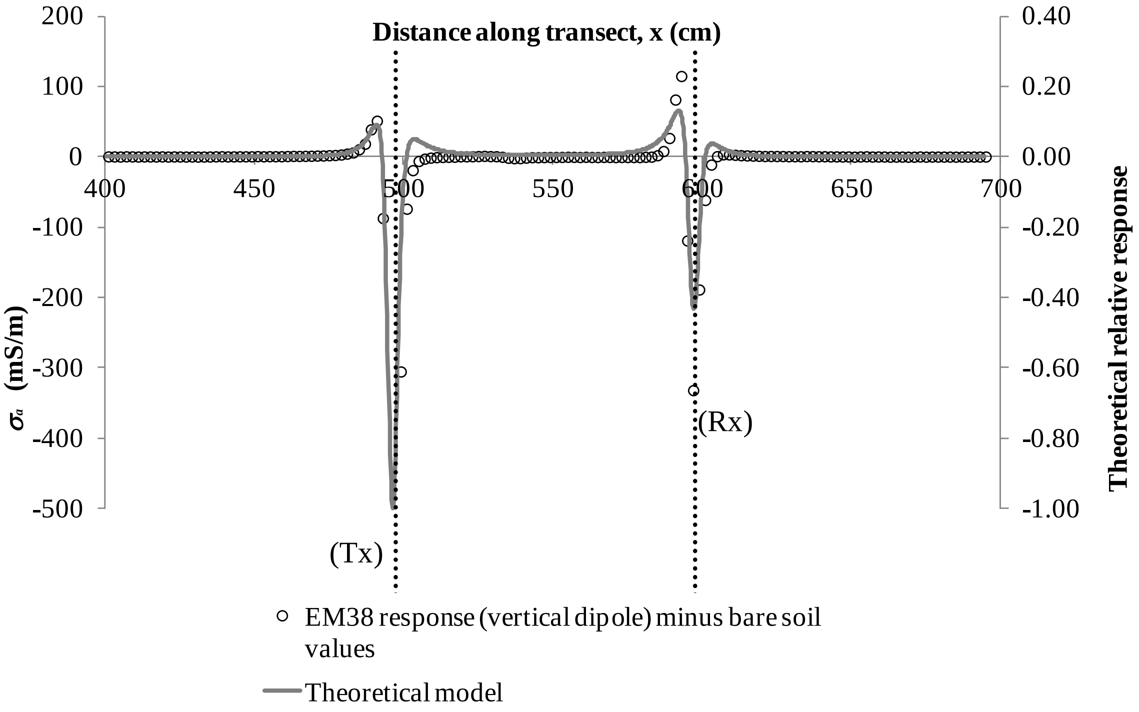

Figure 4. Measured σ_a profile (with bare soil values subtracted) and corresponding theoretical response in the vicinity of the Al access tube location (x = 500 cm). The dotted vertical lines indicate the access tube position when the leading EM38 receiver coil is adjacent (Rx) and when the following transmission coil is adjacent (Tx).

Conclusion

Buried, vertical, aluminium access tubes, typical of those used for neutron soil moisture probes were found to significantly alter the readings of an EMI soil survey meter when located within 50 cm of the tube location. The theoretical model based on a geometry of simple dipole transmitter and receiver coils and a buried cylindrical shell verified the role of horizontal eddy currents in the tube walls in the sensor response. Beyond 50 cm there was no discernible effect on the sensor readings compared to that of the bare soil. Neither the empty holes used to insert the access tubes, nor the widely-used PE or PVC tubes used for capacitance-type soil moisture probes were found to alter the EMI sensor readings, even when the sensor was adjacent to, or over the hole/tube location. If an EMI soil survey is planned in the vicinity of locations containing the aluminium access tubes, either the survey transects must be more than 50 cm away from the tube location, or any data points collected within a 50 cm radius of the location would need to be removed prior to the application of any geo-statistical interpolation procedure. Alternatively a plastic tube can be used, even for the neutron probe provided the impact of the tube material on probe readings are fully understood. Finally, it should be noted that metal access tubes may be ‘visible’ from greater distances if the soil has a lower intrinsic σ_a, although this may, in turn limit the coupling between the access tube and the surrounding soil which may counter the effect. Further work is necessary to investigate this.

Acknowledgments

This work was funded by the CRC for Spatial Information (CRCSI), established and supported under the Australian Governments Cooperative Research Centres Programme. Specific mention of product brand names (Geonics EM38) does not constitute an endorsement of these particular products.

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Appendix 1:C

Site-specific measurements of apparent electrical conductivity (EC_a) correlate to neutron moisture probe counts: Towards the spatial measurement of soil moisture content for precision agriculture.

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Abstract

Precision management of broad acre cropping is limited by our inability to rapidly produce high spatial-resolution maps of soil moisture. We report on a series of site-specific, apparent electrical conductivity (EC_a) measurements using the Geonics® EM38 along with near-simultaneous neutron probe measurements during soil moisture extraction by an irrigated cotton crop. This study differs from previous approaches by using polyethylene neutron probe access tubes so that the EM38 could be operated directly over the soil measured by the neutron probe. We discover strong correlations (average $R^2 = 0.90$) between EC_a and neutron probe counts (NPC) that suggest that EC_a surveys could provide a useful spatial measure of soil moisture. The linear relationships between NPC and EC_a across a range of background EC_a zones for these soils augers well for estimating site-specific moisture content from the coefficient of slope and a site-specific upper limit to EC_a representing field capacity (i.e. full point).

Key Words

EM38, spatial water use, electromagnetic induction survey, neutron probe.

Introduction

Along with soil salinity and texture, soil moisture content has long been recognised as a major component of apparent electrical conductivity (EC_a) as measured by surface electromagnetic induction (EMI) probes (Kachanoski *et al.* 1988; Khakural *et al.* 1998; Hossain *et al.* 2010). Salinity or texture often dominate the EC_a response to the extent that a single electromagnetic induction (EMI) survey, with appropriate ground-truthing, can provide a high resolution map of these variables (eg. Triantafilis *et al.* 2000; Triantafilis and Lesch 2005). However, the less dominant contribution made by soil moisture is often obscured.

The aim of this study was to isolate the contribution by soil moisture to the EC_a response (measured in mS/m) and thereby explore the potential to produce high resolution maps of soil moisture content from EMI surveys. Over relatively short periods, say a few growing seasons, the clay content (texture) and salinity are essentially fixed for any given point in a field. Therefore, repeated measures of EC_a at fixed sites over a short period could be expected to reflect changes in soil moisture. Several other factors influence EC_a including CEC, porosity and pH but these are also essentially fixed for a site (see review by Sudduth *et al.* 2001). Ambient and soil temperatures are the only variables expected to vary significantly over our time frame that have an influence on EC_a (Padhi and Misra 2011).

Measuring the same site repeatedly using the EMI method and a reliable standard is not easy. The usual approaches are compromised. Either; a) the standard interferes with the electrical conductivity meter when used at exactly the same site; neutron probes using aluminium access tubes have this problem; or, b) the standard method disturbs the site forcing future measures to be taken from a different site; soil coring for volumetric moisture content (VMC) presents this problem. In this paper we present correlations between site specific measures of neutron moisture probe counts and EC_a using polyethylene access tubes so that the two instruments can be used at the same location.

Methods

Three, one hectare square plots were marked out across a 96 ha field of Vertosol soil planted to cotton at 'Keytah' (ca. 40 km west of Moree, NSW Australia). Each plot represented an EC_a zone identified from a previous, field-wide, EMI survey (low-plot = 80-120; mid-plot =120-145 and high-plot = 160-185 mS/m).

Ten polyethylene access tubes (56mm dia. x 1.8m) were inserted into the plant line at randomly selected locations across each plot in October 2011, three weeks after sowing. All tubes were inserted to 1.5 m depth, cut off at 20 cm above the soil surface and capped. The field had 1.5 m wide beds, i.e. plant rows were 1.5 m apart with an irrigation furrow between every second row. Furrow run-lengths were 400 m requiring approximately 4 hours to irrigate. EC_a and neutron probe readings were taken at each access tube over a three month period that included four irrigations and several rainfall events. EC_a readings were taken with the EM38 (Geonics® Ltd. Ontario, Canada) in the vertical mode positioned 0, 20, 40,....140 cm above the soil surface (Hossain *et al.* 2010) in line with the plant row and up against the bed-side of the access tube. Sixteen-second counts were taken at 20, 40…140 cm depths using a neutron moisture probe (Hydroprobe® Boart Longyear, Model 503DR, California USA). Both instruments were used at each access tube on ten to thirteen occasions across: January (16,18,20,22); February(16,19,20,22,24); March (2,12,13,14,15); and April (9,10) in 2012.

Data analysis: Neutron probe counts are expressed as ratios of field counts to standard water barrel counts to give a corrected NPC (CNPC). Linear regressions were calculated using R data management software (R Development Core Team).

Results

The combination of EC_a and CNPC that gave the best overall correlation was EC_a held at 20cm above the soil and CNPC averaged to a depth of 40cm (Figure 1). All correlations were greater than 0.75 R^2 and many combinations, where the EM38 was held close to the soil and CNPC averaged to 80cm produced correlations greater than 0.85 R^2. Examples of the data used to obtain these correlations are presented in Figure 2. For clarity, only six sites are selected for figure 2 to show how the relationship lifts for sites with greater EC_a while the linear relationship to CNPC is maintained.

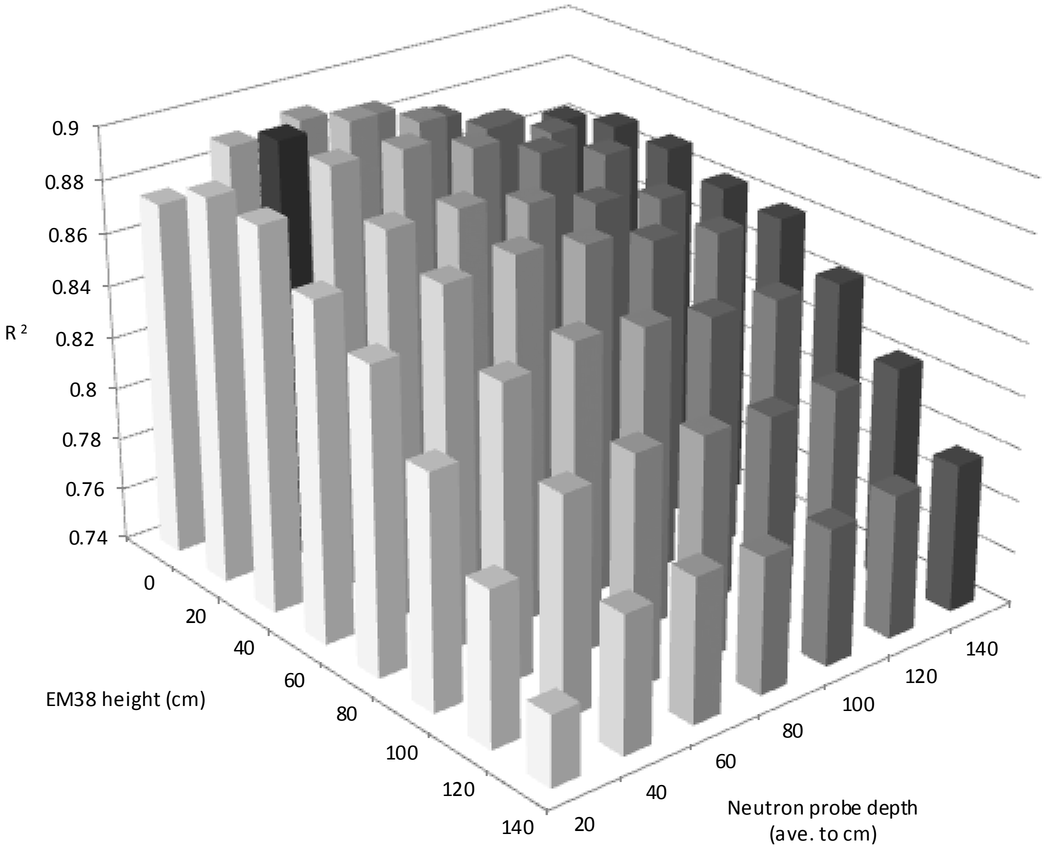

Figure 1. The R^2 for the linear regressions between ECa and corrected neutron probe counts for all combinations of EM38 height above ground and average neutron probe counts to each soil depth. The range of standard errors was 0.009 to 0.024. The dark column at EM38 height 20cm and neutron probe depth average to 40cm represents the 30 tube sites from which the six examples in figure 2 were taken (Std. Error = 0.014).

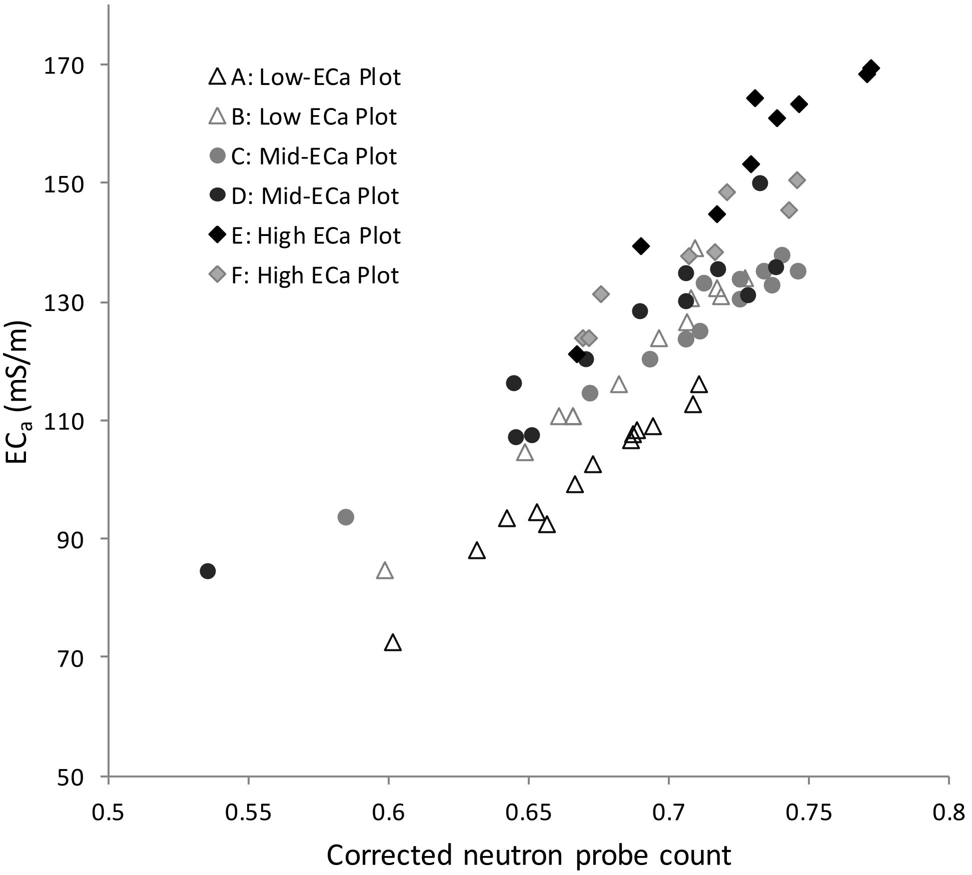

Figure 2. Examples of the linear relationship between EC$_a$ and CNPC for individual tube sites from each EC$_a$ plot for EM38 height 20cm and average neutron probe counts to 40cm. R^2 for: A= 0.98; B= 0.96; C=0.96 D=0.90; E=0.91; F= 0.89.

Discussion

The better correlations corresponded to the shallower neutron probe readings and lower EM38 measurement heights. This is to be expected because the cotton crop was mainly removing moisture from 0 to 60cm and the EM38 is most sensitive to changes in conductivity from 20 to 60cm (McNeill 1992). Furthermore, lifting the EM38 to 20cm served to align the most sensitive region of the EM38 response to the layers of soil where moisture was most variable (Morris 2009). Since the change in EC$_a$ in this configuration explained 90% of all the variation in CNPC, this provides strong evidence that, for these soils and over a reasonably short time frame, EC$_a$ could be used as a surrogate for soil moisture. Sheets and Hendrickx (1995) successfully fitted linear regressions to soil moisture content along a 1.95 km transect using an EM31 and 65 neutron probe sites for calibration over a 16 month period.

The good correlations in the absence of corrections for temperature suggest that a useful indication might be possible without parallel temperature measurements. Sudduth *et al.* (2001) was able to make considerable improvements to EC$_a$ correlations with topsoil depth by simply grouping measurements on whether they were collected when it was ‘hot’ or ‘cold’. Where all measurements are taken across a single season, as for this experiment, the effect of temperature on EC$_a$ appears to be of little consequence.

For many situations in dryland broadacre cropping EMI surveys could provide maps of EC$_a$ rapidly. The strong linear correlations described in this paper auger well for interpreting such surveys as moisture maps. Strategically timed EMI surveys would be needed to identify the range of EC$_a$ for each site. That is, one when the field is essentially at field capacity, shortly after heavy rain, and one when the moisture is severely depleted following a successful crop. These two surveys could identify the limits of field capacity and wilting point for each site or zone in a field for a particular crop. The linear response of EC$_a$ to moisture content would then be applied to future EMI surveys to identify the current moisture content at each site.

Acknowledgments

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Appendix 1:C

SPATIAL APPARENT ELECTRICAL CONDUCTIVITY (EC_a), SOIL MOISTURE AND WATER USE EFFICIENCY IN VERTOSOL SOILS

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ABSTRACT

Producing high resolution maps of water use efficiency (crop yield per unit of water consumption; WUE) for precision crop management is limited by our ability to readily produce maps of soil moisture content. On-the-go grain yield monitors or biomass scans can provide a spatial measure of crop productivity, the numerator of a WUE ratio but water use, the denominator, is limited by physical practicalities to a few single-point measures. Volumetric moisture content inferred from an EM38 electromagnetic induction (EMI) survey, and biomass evolution (Z31-43) derived from optical reflectance measurements were combined for a wheat crop in order to generate a map of water use efficiency (t/ha/mm). Taken over the entire field, the change in soil moisture (mm) was found to explain 38% of the variance in the change in biomass (t/ha). The implications for using multi-temporal EMI surveys in combination with yield maps to produce a spatial measure of water use efficiency are discussed.

Keywords: EM38, spatial water measurement, electromagnetic induction survey, water use efficiency.

INTRODUCTION

Recent and widespread droughts across the cropping regions of Australia have again focused attention on finding ways to maximise the storage and efficient use of soil moisture. Responding to variations in plant available moisture at the sub-field scale could improve water use efficiency but a rapid method of measuring site-specific soil moisture status is needed.

We rekindle the idea of using apparent soil electrical conductivity (EC_a) from electromagnetic induction (EMI) surveys as a surrogate for soil moisture content (Rhoades et al., 1976; Kachanoski et al., 1988; Huth and Poulton, 2007) and apply this to a non-saline, deep, Vertosol soil typical of large tracts of cropping in western New South Wales and south-eastern Queensland, Australia. Hossain et al. (2010) and Padhi and Misra (2011) have correlated EC_a to nearby neutron moisture probe measurements in similar Vertosols. We extend this by attempting to produce a water use efficiency map based on the observed change in soil moisture content estimated from EMI surveys, and the change in above ground crop biomass (productivity) derived from plant canopy reflectance surveys using proximal optical sensors.

For heavy clay soils, moisture seldom reliably dominates the site-specific measurement of EC_a from an EMI survey instrument, such as the EM38 (Geonics®). When not confounded by salinity, cation exchange capacity (CEC) and clay content will contribute the greatest to the EC_a (Lesch et al., 2005; Sudduth et al., 2001). However, soil moisture is likely to dominate a change in EC_a (ΔEC_a) between successive measurements at a particular site because CEC and clay content could be expected to remain constant. Therefore, EMI surveys done at strategic stages in the growing season could potentially be a useful basis for calculating spatial water use efficiency.

METHODS

Site and Surveys

An 18 ha field of black Vertosol was selected at McMaster Research Station (University of New England, Rural Properties) approximately 35 km NNW of the township of Warialda (New South Wales, Australia). A preliminary EMI survey was conducted on the 15th June between sowing and emergence of wheat (*Triticum aestivum* L. *var.* Gregory). Sixty-five kg/ha anhydrous ammonia and 50 kg/ha zinc-mono ammonium phosphate was incorporated prior to sowing. On the 4th Aug, when the crop had reached stage Z31 (first node) the first of two EC_a surveys was performed using a Geonics® EM38 in the vertical mode towed behind an all-terrain vehicle on a 1 cm thick rubber mat. EC_a readings were logged concurrently with DGPS positions (Trimble® TSCe Ranger) and two sets of optical reflectance readings (CropCircle® 'red sensor' comprising 650 and 770 nm wavelength sources and detectors (R_{650} & R_{770}) and 'amber sensor' comprising 550 and 770 nm wavelength sources and detectors (R_{550} & R_{770}). The transect interval was 25 m, the logging interval was 1 per second, and the speed was approximately 10 km/h. The second EC_a and canopy reflectance survey was performed on the 17th September when the crop had reached stage Z43 (flag leaf). No rainfall was recorded at the site over this 6 week period.

NDVI to Crop Biomass Calibration

After each survey, eight sites across the field were selected to represent the range of crop growth. Three randomly selected 1 m^2 areas of crop at each site were then scanned using a handheld variant of the same two CropCircle® sensors (namely red; R_{650} & R_{770} and 'amber' R_{590} & R_{770}). After scanning, all the biomass to ground level was cut and bagged. In the laboratory the biomass samples (all green) were dried at 80^{o}C and weighed. The normalised difference vegetation index for each of the paired wavelengths ($NDVI_{red}$ and $NDVI_{amber}$) was calculated from every instantaneous set of reflectance measurements using $NDVI = [(R_{770} - R_{650\ or\ 590})/(R_{770} + R_{650\ or\ 590})]$ (Rouse et al., 1974). Exponential curves were fitted to determine the correlation between biomass and $NDVI_{red}$ or $NDVI_{amber}$. $NDVI_{red}$ was used to calibrate the first survey and $NDVI_{amber}$ for the second. Kriging software (Vesper®) (Minasny et al., 1999) was used to generate high resolution (10 m^2 pixel) biomass maps for the first and second surveys with a common grid. ΔBiomass between Z31 and Z43 was calculated by subtracting the first (Z31) interpolated survey data from the second (Z43).

EC_a to VMC Calibration

Soil cores (1 m long x 38 mm dia.) were extracted from 5 sites following each survey. The sites were selected to represent a broad range of EC_a from the preliminary survey (15th June). Each core was divided into 20 cm sections and sealed in canisters for later weighing, before and after drying at 110°C. The volumetric moisture content (VMC) (m^3 moisture /m^3 soil) was calculated from the loss of mass during drying (mass of water expressed as a volume) to the volume of the core (20 cm x core cross-sectional area) adjusted for swelling and shrinkage with water content (Yule, 1984). Site-specific EC_a readings in vertical mode were taken at each coring site prior to core removal. Coring after the second survey was done at the same DGPS locations selected for the first survey. Following Hossain et al. (2010), linear regressions were used to correlate ΔEC_a to ΔVMC. The same Kriging software was used to generate high resolution (10 m^2 pixel) VMC maps for the first and second surveys with the same common grid as for the biomass data. ΔVMC was calculated by subtracting the first interpolated survey data from the second.

Data Analysis

Kriging software (Vesper®) was used to generate high resolution (10 m^2 pixel) biomass and VMC maps for the first and second surveys. ΔBiomass and ΔVMC were calculated by taking the first from the second transects measurements determined for each 10 m^2 pixel in the Kriged map. EC_a and NDVI readings for the calibrations with VMC and biomass were independent of the survey data, hence did not involve Kriging.

RESULTS

The linear correlation between ΔEC_a and ΔVMC ($R^2 = 0.58$) was used to generate Fig. 1 which shows the spatial ΔVMC (mm) for the 18 ha field at McMaster Research Station over the six weeks of crop growth.

The exponential correlations between CropCircle® NDVI and green biomass are displayed in Fig. 2. These were used to calibrate NDVI to biomass (tonnes/ha) and calculate the change in biomass (Δbiomass) from survey one to two (Fig. 3).

Fig. 4 illustrates the ratio of ΔVMC to Δbiomass, to produce a map of spatial water use efficiency. Fig.5 shows the correlation between Δbiomass and water use calculated from the pixel values generated by Kriging to produce ΔVMC and Δbiomass maps (Fig. 1 and 3).

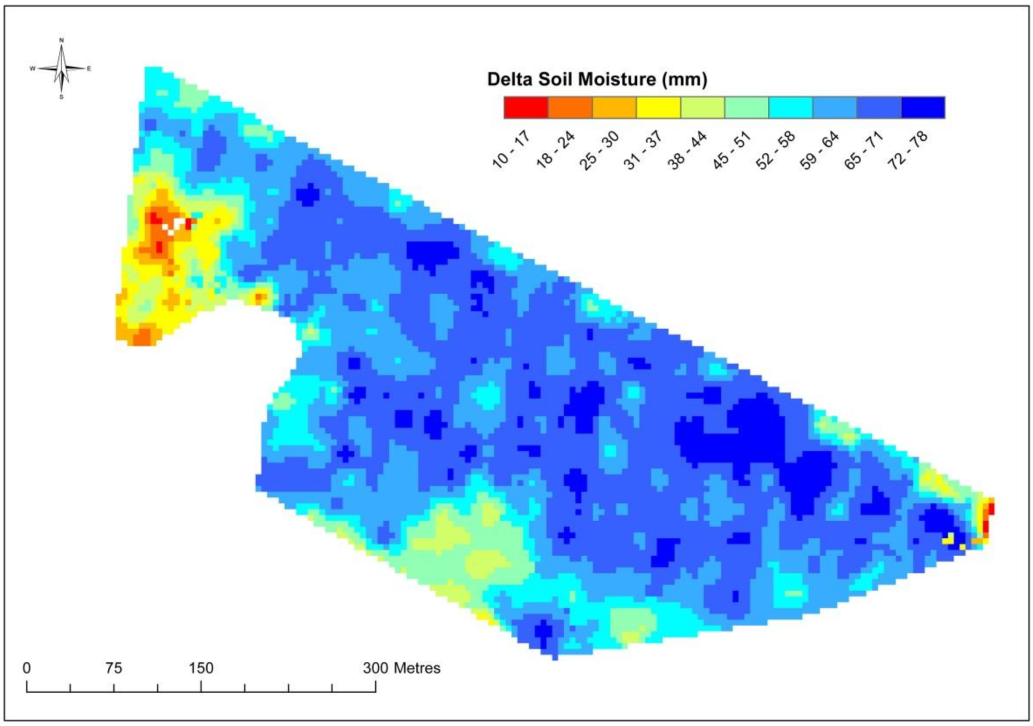

Fig. 1. Spatial change in volumetric moisture content (ΔVMC- mm) for six weeks of growth from Z31 to Z43 for wheat at McMaster Research Station.

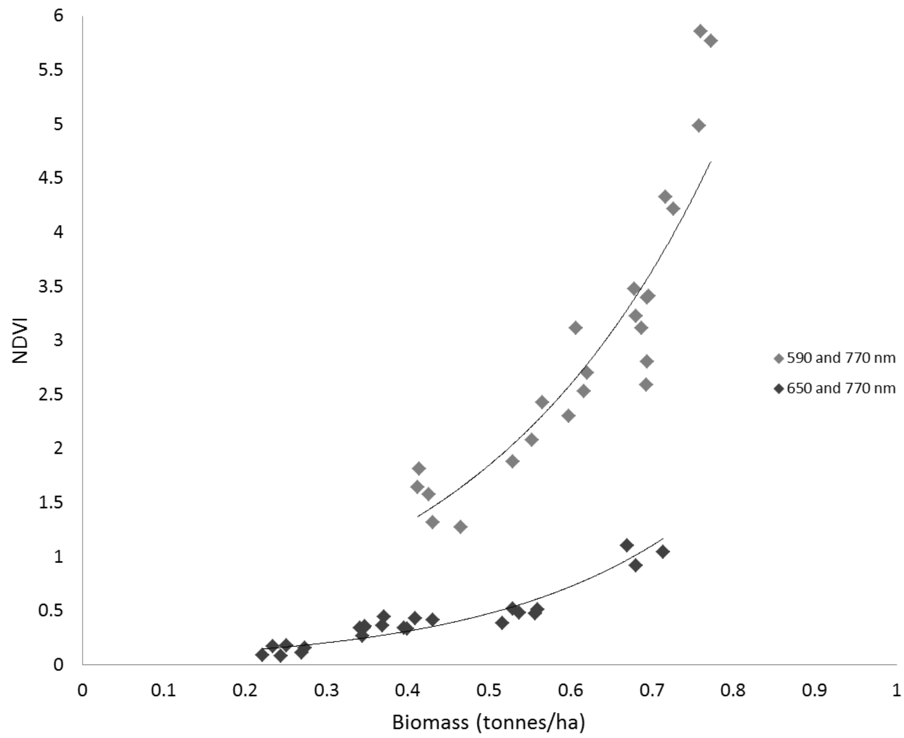

Fig. 2. The correlation between NDVI and biomass using NDVI$_{red}$ (♦ 650 & 770 nm; R^2 = 0.86) and NDVI$_{amber}$ (♦ 550 & 770 nm; R^2 = 0.83) as derived from the CropCircle® optical sensors. Data points derived from both Z31 and Z43 sampling.

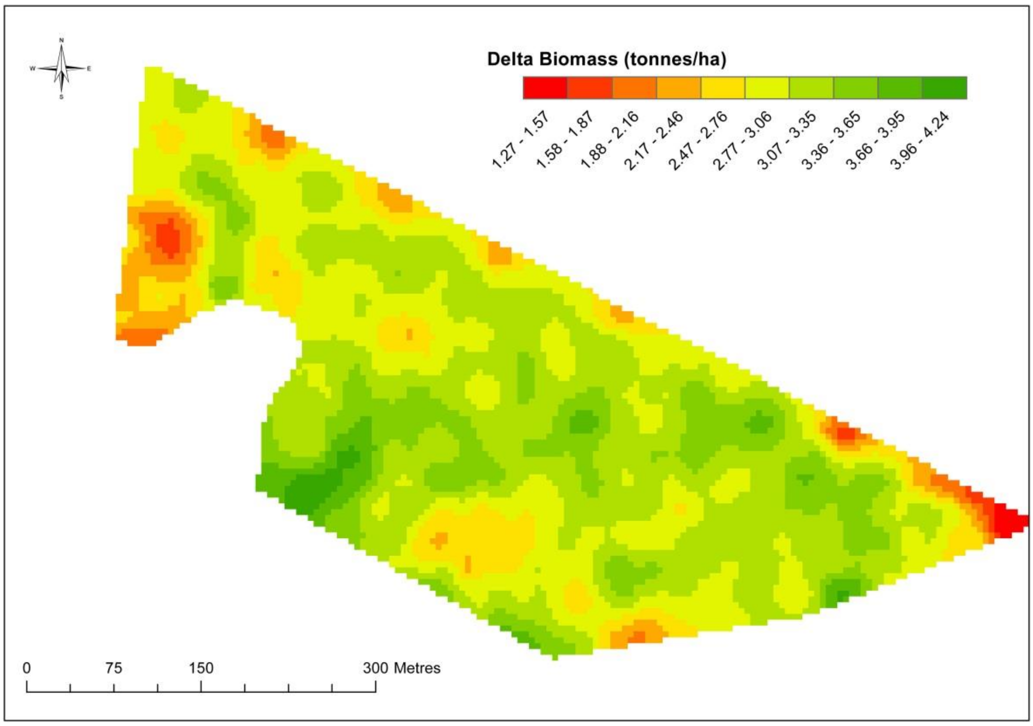

Fig. 3. Spatial change in green biomass (∆biomass- tonnes/ha) for six weeks of growth from Z31 to Z43 for wheat at McMaster Research Station.

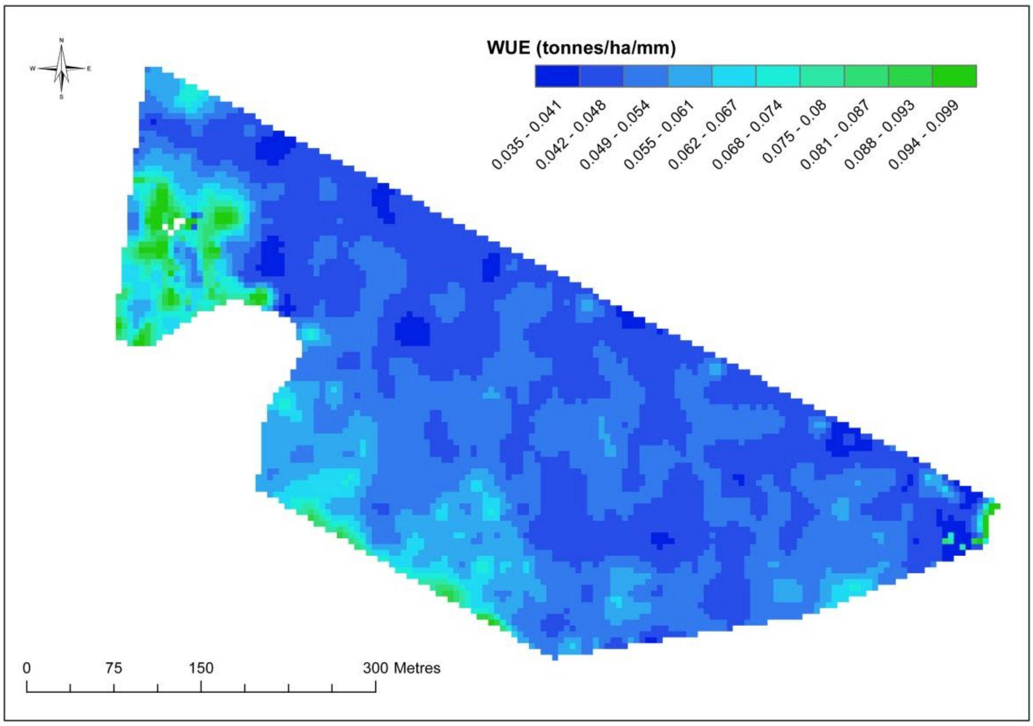

Fig. 4. Spatial water use efficiency for six weeks of growth from Z31 to Z43 for wheat at McMaster Research Station.

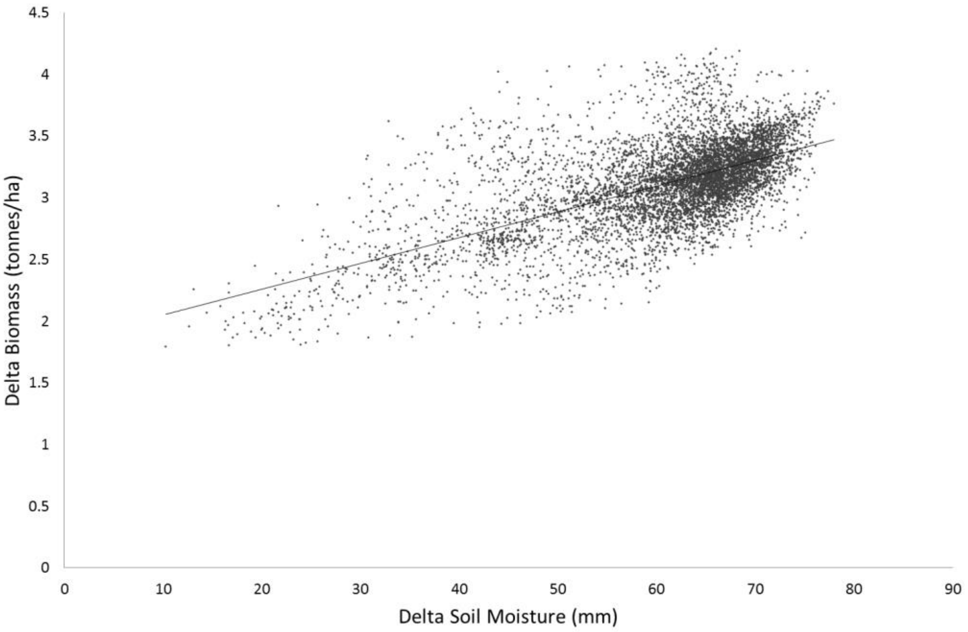

Fig. 5. Linear correlation between the change in soil moisture (∆VMC) and ∆biomass (R^2 = 0. 38) generated from the common grid values that produced Fig. 1 and 3.

DISCUSSION

Single point measures of soil moisture content from neutron, capacitance or resistance based moisture probes cannot provide measurements for enough locations to generate a high-resolution spatial measure of soil moisture. Using EC_a as a surrogate has suggested a three-fold and patchy difference in crop moisture use across the field (Fig. 1). This alone suggests that different sections of the field are behaving differently and might benefit from site-specific management. Our efforts to correlate EC_a to moisture were not extensive and were not intended to reaffirm the correlations from other research (eg. Hossain et al., 2010; Padhi and Misra 2011) but gave our estimates comprehendible units. The relative differences are probably more reliable than the absolute estimates.

If the differences in water use reflect fixed insurmountable differences in potential productivity, for example subsoil constraints like high salinity (Dang et al. 2011) or simply lower initial water status, the poorer areas could be sown at rates that match their potential, even zero sowing if uneconomic production is predicted. But perhaps the poorer water use areas are reflecting poorer nutrient levels. In this case variable rate in-crop fertilisers could be expected to boost production.

Using NDVI as a surrogate for biomass provided a reliable calibration and indicated a patchy and three-fold difference in crop growth across this field (Fig. 3). This also suggests that site-specific management could improve the efficiency of crop production in comparison to even applications of inputs. Using both $NDVI_{red}$ and $NDVI_{amber}$ provided the opportunity for extended dynamic range of sensor performance at the higher biomass levels encountered.

Putting water use and biomass together to generate a map of water use efficiency has produced an interesting result; namely it has evened out the individual spatial differences (Fig. 4). In other words, the availability of water in the field has largely affected the evolution of biomass; with exception of small areas of very high water use efficiency evident around the perimeter. These correspond with areas that produced very low biomass. The absolute moisture content could help to explain the WUE. Including strategic EMI surveys when the soil is very dry and wet to determine the full and wilting points respectively would allow estimates of absolute soil moisture content from site-specific EC_a readings. Note that care is also needed when interpreting these areas as high crop production because small plants, albeit making the most of what might be low-moisture availability, might not reach harvest.

As expected, biomass production correlated with water use, but the change in water content only explained 38% of the variance (Fig. 5). A large number of other factors, including measurement errors explain the residuals. Nonetheless, the question as to whether 38% is some surrogate measure of water use efficiency, in terms of how much change in biomass is explained by change in VMC, remains and is worthy of further investigation. Real differences in cropping potential should be explored where the surveys highlight differences. There are also steps in the data collection and analysis that could be improved to minimise errors. The transects followed in the second survey were the same as for the first. Beyond using the same transect map the vehicle tracks remained visible from the first survey to be followed in the second. However, small differences in tracking of the EM38 and NDVI sensors could be explored to make sure they correspond to exactly the same field positions. The importance of these factors depends on the rate of change of real field values relative to the accuracy of the GPS.

A spatial measure of water use efficiency could be useful at the research level and for producers. Plant breeders might be able to screen larger areas of crop for genotypes with better WUE. Producers would be able to identify practices that generally give higher WUE for their soil, crop types and seasonal variation. Plant available moisture is the major determinant of crop yields in Australia. Revealing the extent to which water use efficiency varies between practices for specific farming regions is the next step towards identifying practices that lead to greater efficiencies.

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