

MEASURING SOIL WATER USING EM38 TECHNOLOGY

2 day workshop Toowoomba, Qld
20 - 21 July 2015

Workshop manual



CONTENTS

Workshop overview.....	3
EM38's - what they measure and how they work.....	4
Measuring soil water	4
How the EM38 works.....	5
How do we get a soil/paddock calibration for estimating soil water?	5
What about soil texture variability in my paddock?	7
Temperature effects on the EM38 readings.....	7
What if I don't have a paddock calibration (qualitative versus quantitative use)	7
Case study - monitoring soil water in a cotton crop using an EM38.....	7
Soil calibration procedure.....	8
Monitoring the crop throughout the growing season.....	9
Calibration validation.....	10
References.....	11
Using EM38 in the assessment of watering requirements of floodplain vegetation.....	12
Introduction	12
Materials and Methods	13
Results and discussion.....	15
Rapid soil water monitoring using EM38.....	18
Introduction	18
The EM methodology.....	18
What can I do with this information?	21
Pros versus Cons	21
Diagnosing traffic based soil compaction with an EM38.....	22
Introduction	22
Theoretical concept.....	22
Methods.....	24
Results and discussion.....	24
Conclusion.....	27
Identifying a non-destructive technique to assess nematode tolerance in wheat variety trials.....	28
Introduction	28
Methods.....	29
Results and Discussion	29
Conclusions.....	31
Using EM 38 for detailed study of soil water in wheat	32
How to make a pretty picture, from start to finish using Dat38MK, Vesper and ArcGIS	34
DAT38MK.....	34
VESPER.....	36
ArcGIS 10.2.1.....	40
Depth response function of the EM38	42
EM38-MK2 Approximate range of sensitivity and response function.....	44
Temperature correction factors calculated for a range of locations in eastern Australia.....	45
Soil sampling for volumetric water content.....	46
The journey to commercialising this technology in the dairy industry.....	48

Workshop overview

The irrigated cotton industry of Australia faces ongoing pressure to adapt farming practices to improve water use efficiency. This has become necessary because of water shortages due to droughts, changing climatic regimes, increasing competition between water users and water buybacks.

Cotton farmers place high importance on improving their use of water, yet essential elements are still lacking within the area of on-farm soil water monitoring. Currently farmers have few ways of accurately linking their irrigation applications (when to irrigate and how much to apply) to known soil water deficits throughout the growing season. This is largely because measuring soil water is difficult, particularly for the swelling clay soils found in the irrigated cotton growing areas of NSW and Queensland. Both capacitance and NMM technologies used in the industry to monitor soil water have known drawbacks in these soil types and usually have not been calibrated for each soil and therefore data provides information on trends only. Paddock plant available water capacity (PAWC) cannot be determined from the uncalibrated data, nor soil starting water, the volume of water needed to refill the soil deficit or the quantity of water percolating to various depths in the soil after irrigation.

Among the suite of soil water monitoring instruments currently available, one that stands out and is increasingly being used by researchers and agronomists is the EM38 (Geonics Ltd., Ontario, Canada). This electromagnetic induction instrument is being used in a wide number of agronomic and environmental applications to monitor soil water within the root zone. It provides an efficient means to monitor crop water use and plant available water (PAW) in the soil profile throughout the growing season. EM38 datasets have also proved valuable to test and validate water balance models which are used to extrapolate to other seasons, management scenarios and locations.

There is plenty of capacity within the industry to improve soil water monitoring using newer approaches. However to do this, access to current scientific and technological information is needed. In February 2015 a group of cotton researchers travelled to three cotton regions (Central Qld, Gwydir and Macquarie Valleys) to showcase the latest irrigation scheduling and automation technologies as part of a 'Cotton Irrigation Technology Tour'. A series of post Tour workshops are now being run in response to demand generated for training in the application of these technologies (including EM38 technology used for soil water measurement). This workshop aims to provide accessible, hands-on training to researchers, consultants, agronomists and growers (across a range of industries) in using innovative EMI technologies to monitor soil water.

EM38's - what they measure and how they work

By Jenny Foley, Department of Natural Resources and Mines, Qld.

In Brief ...

- EM38's are instruments used by researchers, agronomists and growers to provide rapid and reliable information on soil water within the root zone
- They are recommended for use in the industry after many years of successful use in research trials, either as a stand-alone method to monitor soil water or as part of an integrated combination of methods
- They provide accurate estimates of soil PAW so that informed management decisions can be made e.g. the application, timing and conservation of irrigation water and fertiliser.

EM38's are easy to use, lightweight, and provide rapid, numerous measurements over large areas without the need for ground installations or destructive sampling. They also have none of the wiring, electronic logging or access tube requirements of other monitoring technologies. Information can be gathered rapidly for a large number of sites. With new advances in EM38 technology, survey and GPS receiver information can also be recorded in the paddock using held computer acquisition systems. There is a labour component required to taking EM38 readings. The instrument cannot be used remotely. However, this means it is also mobile and the advantage of this mobility is that it allows numerous readings to be taken across a paddock. Instantaneous readings can be viewed on-screen as the operator walks through the paddock and literally hundreds of reading can be taken in a short amount of time.

Measuring soil water

Like all other soil water monitoring devices on the market, EM38's do not directly measure *soil water*. The only way to directly measure soil water is to take a soil core. Soil water monitoring devices actually measure other attributes of the soil, which can be related to soil water via a soil calibration.

Capacitance probes (e.g. C- Probes, EnviroPro) measure the soil dielectric, or the ability of the soil to store a charge; neutron probes measure neutron scattering; TDR probes measure the transmission time of the soil to return a current; and EM38's measure the size of the magnetic field induced by transmitting a current through the soil, called the *apparent electrical conductivity (ECa)*.

One of the main problems growers run into with capacitance devices is that only small volumes of soil are being measured at a few locations in a paddock. These values may have to represent what is going on across the whole paddock (so probe positioning is very important). They may also have problems on clay soils with cracking around the access tubes which can create artefacts in the readings. Air gaps and cracks around the access tube prevent the device from 'seeing' soil and may result in null readings. Over-wetting the soil may also happen during irrigation because water runs down the cracks. The EM38 avoids these problems because it doesn't need to be installed in the paddock and each reading is an average for a large soil volume (>1 m length).

How the EM38 works

EM38's measure electric currents induced at depth in response to an external magnetic field. The strength of the induced current is determined by the apparent electrical conductivity (EC_a) of the soil. Different orientations, coil offsets and depths measured (ground level or above) are used to obtain a range of sensing depths. The EC_a reading is a weighted average across a depth range, weighted according to the respective depth functions of the different coil orientations and spacing's (Figure 1. The depth response functions for individual depths down the soil profile are also provided in the manual).

In the vertical dipole (EM38 placed upright on ground surface) the reading is weighted strongly towards soil attributes at around 0.3-0.6 m depth, declining exponentially to approximately 1.5 m depth (1 m coil spacing). When the device is placed in the horizontal dipole mode (EM38 sideways on ground surface) the reading is weighted strongly towards soil attributes at the surface 0-0.3 m, declining exponentially to approximately 0.75 m. Targeted readings can be taken for the purposes of tracking soil water movement and redistribution at depths of most interest to the operator by simple choice of dipole, coil spacing or height above ground.

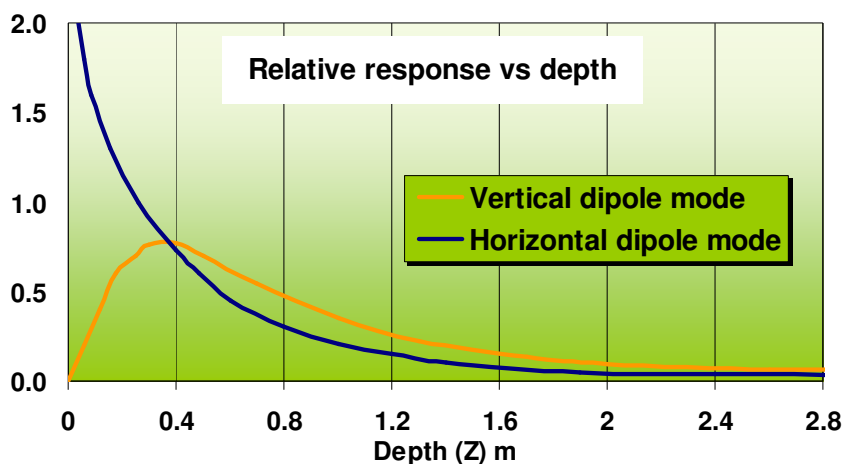


Figure 1. Depth response functions for an EM38 used in either the vertical or horizontal dipole mode

How do we get a soil/paddock calibration for estimating soil water?

The electrical conductivity of soil is primarily a function of the clay content and type, porosity, the salinity of the pore water and the degree of saturation. There are also other factors that can influence the electrical conductivity of the soil but these are not significant in the context of measuring soil water. Clay soils are better conductors than sandy soils because they naturally hold more water and the pore spaces within the soil are mostly small and water filled. Whereas the pore spaces in sandy soils are mostly large and air filled (and air is not a conductor). Salts in the soil water also increase the conductivity because they turn the water into a highly conductive electrolyte.

For any given paddock the only variable that will change significantly during a growing season or watering cycle is the degree of saturation. As the soil becomes saturated the electrical conductivity of the soil will increase (Kelly and Acworth, 2005).

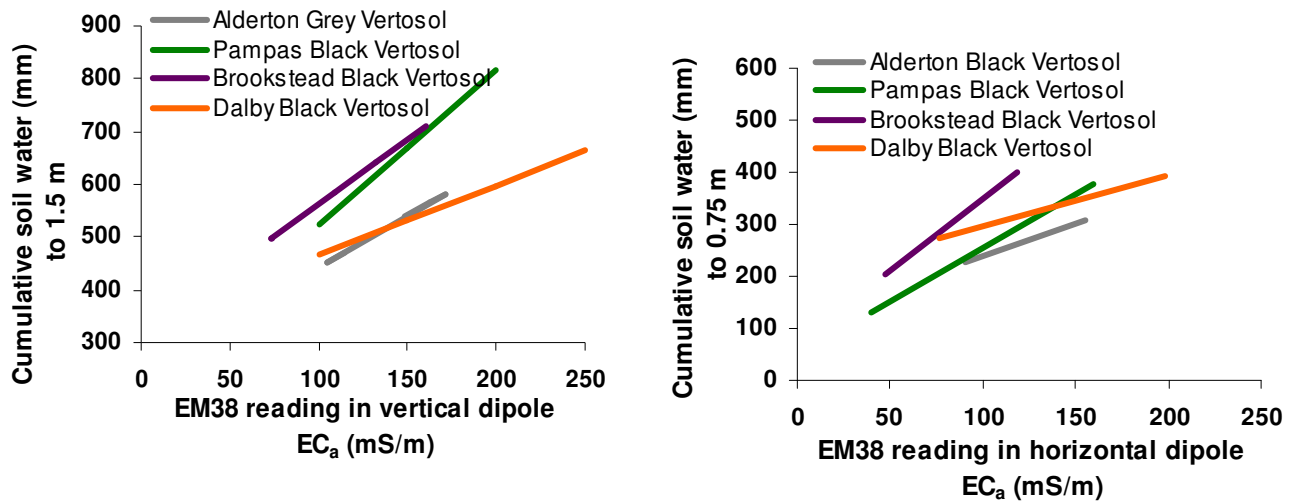


Figure 2. EM38 readings calibrated against soil water for southern QLD Vertosols - showing variation between sites and soil types for both vertical (1.5 m) and horizontal (0.75 m) dipoles

To track water movement and re-distribution throughout a growing season, repeated measures at the same locations within the paddock (with salt and clay remaining constant) allow for any changes in EC_a to be attributed to changes in soil water content. We can convert this to mm of stored water by using a simple soil calibration. This is actually a simple linear relationship between the EC_a reading and the total mm of soil water within the depth of measurement. With a soil calibration we can take a reading and then look up the corresponding mm of soil water to a certain depth in the soil profile. It varies from one soil type to the next as we can see in Figure 2. It changes with clay content, soil texture and other properties.

To get a soil calibration, EM38 readings and soil cores are collected together. The soil cores are weighed before and after drying (giving a mass of water per unit mass of dry soil). The core length and diameter are also measured at the time of core sampling in the field, to be able to later calculate the soil bulk density. This allows us to convert gravimetric soil water to volumetric soil water content (volume of water per total soil volume). This is what the instrument actually ‘sees’. Sampling at a range of wet to dry paddock conditions provides the best calibration e.g. after irrigation and after harvest. A single calibration can be used for each paddock or the whole farm if the soil is reasonably uniform. As few as six sampling points gathered across a range of soil moistures may be sufficient to develop a calibration that provides a very good estimate of soil water.

Once we get a calibration for a paddock, or whole farm, we have it for life. The calibration will only be affected by things that significantly alter the soil texture (major earth works) or the amount of salt in the soil (for example - switching irrigation water supplies from clean to salty water, or vice versa).

The EM38 can be towed along a survey line in a paddock while the PC records the GPS and EC_a data. A map of soil texture can then be generated using free software available on the web. This map can also be converted to a map of stored water in the soil (mm) by using the soil calibration.

What about soil texture variability in my paddock?

When we measure EC_a across a paddock with variable soil texture, differentiating soil water content from other attributes becomes increasingly complex. An increase in EC_a may be due to an increase in water content, or salinity or it may be due to an increase in clay (which is often accompanied by increased water and salt). Some care must be taken when interpreting readings in these conditions. Applying a paddock calibration to derive soil water becomes hazardous unless detailed mapping of soil zones, verified by soil surveying, is undertaken and separate calibrations developed for the different soil zones. This requirement, however, is similar for other methods of soil water measurement.

EM38's are ideal for use on clay soils. They are not suitable for use on iron rich soils, as the iron in the soil interferes with the instrument's electromagnetic frequency. Most red soils are rich in iron.

Temperature effects on the EM38 readings

Soil temperature is dependent on time of the year, local climate and paddock conditions. Due to the temperature dependency of EC_a , a soil correction factor needs to be used to adjust readings for soil temperature variations. This is only required if measurements are taken throughout the year. Tables of representative correction factors have been published for sites within the northern grain growing region. Refer to the additional notes at the end of this manual, where temperature corrections for a range of locations are provided (Table 2 from Huth and Poulton, 2007).

What if I don't have a paddock calibration (qualitative versus quantitative use)

The EM38 can be used to enhance and support our instinct, experience and knowledge. By simply walking in the paddock during fallow and cropped conditions with the EM38, changes in soil water and EC_a can be observed (readings are instantaneous and can be viewed continuously on screen). Over time the operator will come to know both the degree of paddock variability, and the expected EC_a for a range of moisture conditions for a particular paddock or whole farm. This range will encompass typical readings when the soil is drier e.g. harvest and potentially a crop lower limit, and typical readings when the soil is wetter e.g. at sowing, and potentially when the soil is close to drained upper limit. If an absolute value of PAW (mm) is not required, then this 'qualitative' approach is often sufficient. From this type of application, a very useful qualitative estimate can be made about the PAW and how full the 'bucket' is. More information on this is provided in the section by Neil Huth.

Research usually requires very accurate 'absolute' values and soil specific calibration, whereas, crop monitoring can utilise 'relative' values to measure long-term changes in the soil moisture.

Case study – monitoring soil water in a cotton crop using an EM38

Infiltration of irrigation water, and soil water extraction by plants, are key components of the water balance of cotton crops. They are difficult to measure because measurements need to be repeated over time and made at a range of depths in the soil, and because access is difficult when fields are wet. We used an EM38 (single 1 m coil) to estimate infiltration and crop extraction during a cotton season to provided data for modelling validation (Foley et al. 2012; Mills et al. 2008).

We tracked water content changes across a paddock at Pampas, Queensland, on a Black Vertosol soil, where variability in soil moisture was seen between rows and furrows and also from the head to the tail ditch. We also raised the instrument above ground (inversion method or ‘depth slicing’) to get depth discrete soil water profiles for a better interpretation of the EC depth distribution (Rhoades and Corwin 1981; Cook and Walker 1992; Hossain *et al.* 2008).

Soil calibration procedure

EC_a readings were calibrated against cumulative soil water for a range of wet and dry field conditions (Figure 3). Soil cores were taken with a soil coring rig to 3 m depth and bulk density and gravimetric water content sampled in 0.2 m increments. Samples were also taken for chemistry analysis to check for variability in clay and EC between sampling sites. Several adjacent paddocks were sampled to get a good range of moistures, including post harvest in zero till sorghum (at CLL); our experimental PAWC plots (at DUL); bare fallow (filling); the cotton crop after an irrigation (wet to saturated); and native vegetation (very dry).



Jenny Foley taking soil cores to measure volumetric water content under the cotton crop



Maria Harris (DNRM, Toowoomba) using a grid layout for taking EM38 readings in the cotton crop

EC_a (mS/m) measurements from the EM38 were converted to mm of water by regression of the EC_a readings against volumetric water contents (for discrete soil depths), for the range of wet to dry field conditions. EM38 readings were taken in vertical and horizontal dipole modes at ground level, and at 0.1 and 0.4 m above ground. Head and mid positions in the cotton crop were sampled for calibration purposes soon after the second irrigation, while soil was still above DUL.

In the vertical position, the EM38 effectively measures EC_a to 1.5 m, while in the horizontal position, to 0.75 m. Raising the device above the ground is equivalent to ‘shunting’ the EC_a profile lower down the EM38 depth response function (Hossain *et al.* 2008) i.e. in the vertical mode, a reading 0.1 m above ground now measures to a bulk depth of 1.4 m (1.5 m minus 0.1 m), and at 0.4 m above ground to a bulk depth of 1.1 m. Therefore, to determine calibration equations for 6 depths in the soil profile, mm of soil water were calculated from volumetric water contents and summed to each depth (0.35, 0.65, 0.75, 1.1, 1.4 and 1.5 m), then compared by regression with the EC_a measurements.

The relationship between EC_a and cumulative volumetric soil water content was highly significant (F pr. <0.001) and strongly linear for vertical and horizontal modes ($R^2=0.84-0.95$) (Figure 3). As there were slight differences in the slopes of the individual calibration regressions, 6 separate calibrations were used to convert all the data into mm of water. The calibration was highly sensitive to cumulative soil water depth, indicating the need for precise sampling and accurate calculation of soil water.

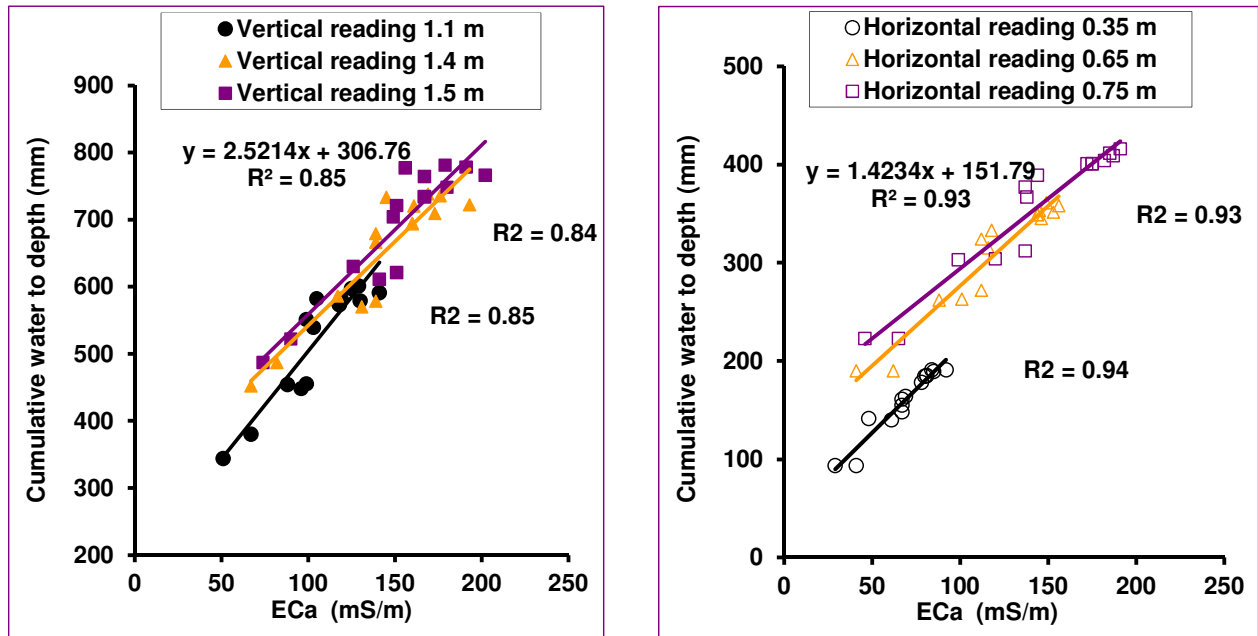


Figure 3. Soil calibrations for ground and above ground EC_a readings in vertical and horizontal dipoles

Monitoring the crop throughout the growing season

EM38 readings were taken in a grid pattern at head mid and tail positions (96 readings at each position) throughout the growing season. The collection of readings (32 points at 3 heights in 2 modes in each location) was rapid, taking around half an hour in each location of the paddock.

For each paddock location (head, mid, tail, row, ditch) 4 measurements were needed in vertical mode to get an average that was within 5 mS/m of the true mean. In horizontal mode, 15 measurements were needed for the same accuracy. The greater number of samples required in horizontal mode is presumably because the surface soil had more variability due to cracking and roughness. In larger areas, it is important to consider the spatial distribution of water, salt and clay in the soil when sampling.

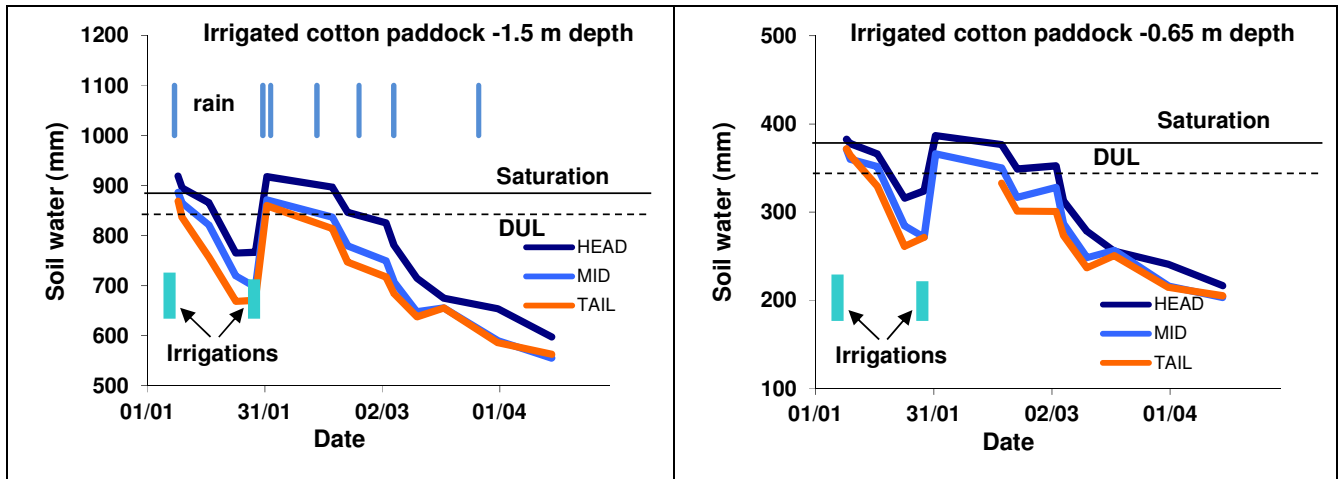


Figure 4. EM38 readings are converted to stored soil water. Soil water, distribution of irrigation water and paddock variability is monitored for an irrigated cotton crop on a Black Vertosol soil. Note the variability in total infiltration after irrigations (head gets more water than mid or tail), the degree of over watering (at head of paddock and this was accompanied by visible plant stress from water logging), and the total crop water use over the growing season

In Figure 4 we see the variability in total infiltration after irrigations (head gets more water than mid or tail), the degree of over watering (at head of paddock and this was accompanied by plant water logging), and crop water use over the growing season. The soil was above DUL for much of the time (i.e. it was probably draining much of the time). The soil was saturated to considerable depth after each irrigation, especially near the head ditch. Despite being wetter, the soil at the head ditch end of the paddock lost water at a similar rate to the mid and tail positions. The mid and tail appear fully watered (or wetter) while the soil near the head ditch is too wet for too long. This is consistent with the unhealthy plants that were seen in some areas near the head ditch that were probably waterlogged.

About half of the irrigation water applied at the end January appears in the 0.65 m to 1.5 m zone (i.e. the rise in the graph to 1.5 m is about double the rise in the graph to 0.65 m). This is a concern, as there are not as many roots at this depth as there are close to the surface, and water added to this depth is more likely to drain from the profile rather than be used by the crop.

The EM38 monitoring highlighted how wet the soil was until late March. Some of this was due to rainfall soon after the irrigation in late January, but it appears that the irrigation was going to be somewhat earlier than necessary. The soil moisture deficit in late January was small when compared with later in the season.

Calibration validation

Two years after this study was completed one of the paddocks used in determining this soil calibration was re-examined in a separate study (in the paddock where the PAWC data was collected) (Foley et al. 2012). During this study, a number of soil cores were taken for soil volumetric water and soil chemistry at mid and tail positions in the paddock. This provided an ideal opportunity to validate the original calibration. At each core location EM38 readings were also taken.

The original soil calibration predicted a total cumulative soil water in the top 1.5 m to within 4% of the averaged total soil water measured from the soil coring (24 mm under predicted); and to within 1% of the total soil water in the top 0.75 m (3 mm under predicted). This is equivalent to an average (under-prediction) of soil water with depth of only 1.6% in the top 1.5 m (vertical dipole) and 0.2% in the top 0.75 (horizontal dipole). This is an extremely high level of accuracy, usually unseen outside of detailed and accurate direct soil coring measurements.

This validation suggests there is a high level of temporal and spatial robustness in this particular calibration when applied across the local environment (uniform Black Vertosol soil). The 'farm' soil calibration was determined from sites spread over ~1 km in the landscape and then validated in this study two years later.

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Using EM38 in the assessment of watering requirements of floodplain vegetation

By Mark Crawford - Department of Natural Resource and Mines, QLD

This research forms the basis for "The implications of gilgai on electromagnetic induction measurements with EM38 in the Borders rivers region". Submitted to the 2015 Australian Cotton Research Conference, "Science Securing Cotton's Future ", 8-10 September 2015, USQ Toowoomba Campus, Queensland, Australia.

In Brief....

The EM38 is a useful tool in the assessment of water requirements to maintain the condition of the main floodplain tree species in the Lower Balonne. The results from three sample dates demonstrate a clear pattern of mound and depression and the wetting up patterns after rainfall. Spatio-temporal moisture dynamics, microrelief patterns and subtle effects on water movement in the landscape caused by gilgai can be identified.

Introduction

Developing an improved Basin-wide conceptual framework that supports understanding of floodplain vegetation water requirements, including water source partitioning, and how these vary spatially across the Basin is essential to the continued management of the Murray Darling Basin. Environmental variables such as landscape position, soil type, and groundwater regime are key in the knowledge-driven environmental assessment process. The "Watering requirements of floodplain vegetation asset species of the northern Murray-Darling Basin" (Floodplain Vegetation) project is being undertaken as a part of the Australian Government's larger Murray-Darling Basin Environmental Water Knowledge (MDB EWKR) project. It is therefore vital that the uncertainty surrounding the watering requirements of floodplain plant species in the northern MDB (river red gum, coolibah, black box and lignum) be clarified as to enable the environmental assessments of Queensland and NSW MDB water resource plans. The environmental assessment process requires specific understanding of local eco-hydraulic requirements of assets to define opportunities for relevant ecological responses and understanding of the frequency with which such opportunities are required to maintain viable assets – in this case the condition of floodplain vegetation asset populations - and achieve plan outcomes.

The aim of the project is to assess the water requirements to maintain the condition of the main floodplain vegetation species in the Lower Balonne. This will include assessment of the required frequency, duration and maximum period between flood events to avoid undesirable decline in their condition, and the dependency of vegetation on surface and groundwater (to the extent possible in the time available). The aim of the EM surveys was to support traditional survey techniques while determining spatio-temporal moisture dynamics, if micro-relief could be identified and how soil properties influence the EMI signal under natural vegetation conditions.

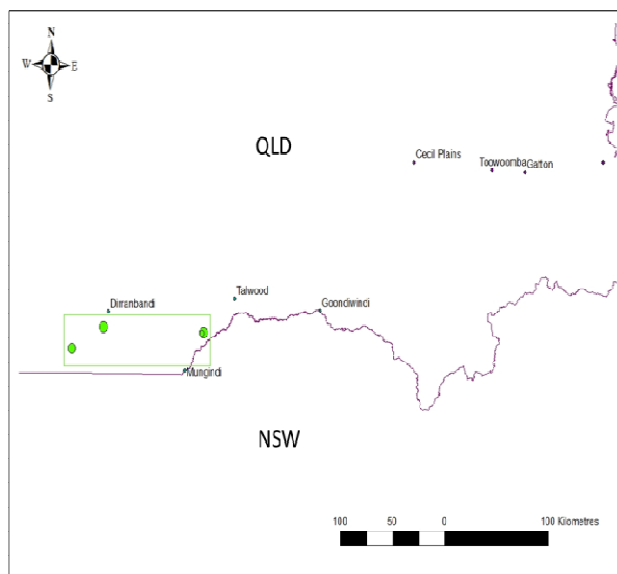
Materials and Methods

General Approach

The project will undertake a program of remote sensing, on-ground monitoring, GIS analysis, groundwater modelling and vegetation condition modelling in order to:

- Identify eco-hydrological correlates of floodplain vegetation distribution and change in floodplain vegetation condition through time in the study area and identify and quantify vegetation water use
- Identify and quantify the influence of river flooding on water availability in shallow aquifers and unsaturated root zones
- Develop models capable of predicting vegetation condition responses to alternative flow management scenarios.

Site description



The Condamine-Balonne region lies mainly in southern Queensland and extends about 100 km south-west into New South Wales. The major waterways in the region are the Condamine, Balonne and Maranoa rivers. Two site locations were situated 15 and 50kms SW of Dirranbandi, with other sites from a related project in the Border Rivers catchment 40kms SW of Talwood (Figure 1). The soil types included Grey and Brown Vertosol and a Black Chromosol overlying sand. Vegetation included moreton bay ash, coolibah, brigalow, belah and lignum (Figure 2).

Figure 1. Study Area (4 site locations)



Figure 2. Euraba Road. Left: Green Moreton Bay ash and coolibah, middle of sand ridge, highest elevation. Right: Dry coolibah/lignum on Grey Vertosol in lowest part of the landscape, west side of sand ridge.

EM38 Surveys

The EM surveys were used to support traditional soil survey methods and identify spatio-temporal moisture dynamics of the selected sites, if micro-relief could be identified and how soil properties influence the EMI signal under natural vegetation conditions. The EM38 survey at Euraba Road consisted of 10 m intervals in the vertical dipole within a 700m x 150m extent. The raw data was then processed in the spatial prediction PC program Vesper (Minasny et al., 2005) using a local variogram and 15m block kriging, interpolated onto a 1 m grid (Figure 3). In the assessment of microrelief at the Euraba Dry site a 1 m interval in the vertical dipole within a 100 m x 100 m extent was also collected. The raw data was then processed in Vesper (Minasny et al., 2005) using a local variogram and 2m block kriging, interpolated onto a 1 m grid (Figure 4).

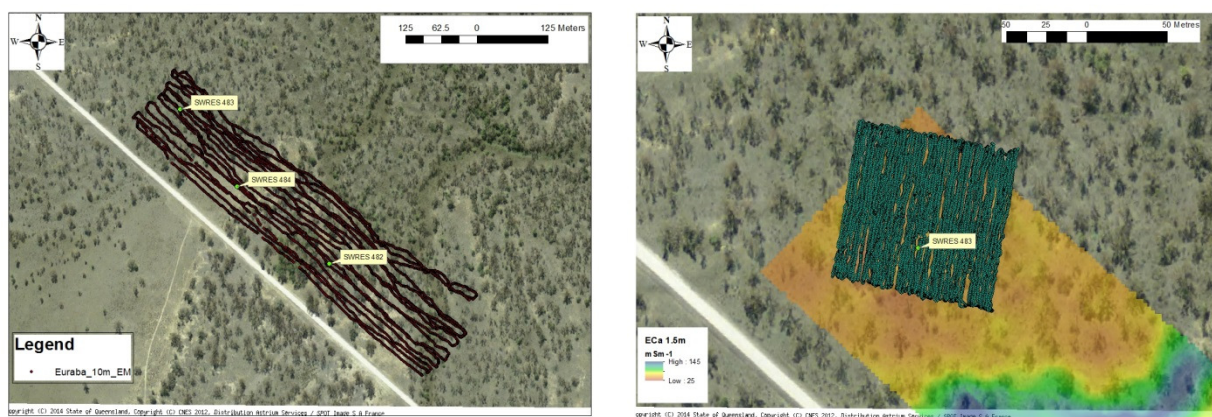


Figure 3. Left: EM38 10 metre (m) survey conducted at Euraba road site. Right: EM38 1 m survey conducted at Euraba road dry site.



Figure 4. EM38 1 m interval survey conducted at Merriot road wet site.

Soil Sampling

Soil sampling was carried out at selected survey times to depths of 2-3 metres. Bulk density, Particle size analysis (PSA), electrical conductivity (EC), chloride (Cl) and volumetric moisture were sampled in 10 cm increments and assessed to help with the interpretation of ECa maps.

To assess the change in soil water over time in native vegetation (belah/brigalow) with gilgai microrelief, a 1 m interval, 80 m x 80m extent survey was conducted in the vertical dipole (Figure 4) at the Talwood sites. The dates were chosen to represent a wetting up of the profile with rain falling after the initial survey date (25/02/2015). Rainfall occurred (84mm) 10 days before 2nd survey on the 14/04/2015 and 62mm 7 days before the 3rd survey on the 23/06/2015. Data processing was the same as the 1m surveys at Euraba road.

Results and discussion

The results thus far have demonstrated the usefulness of ECa imagery in the identification of soil type changes and the presence of microrelief at the Euraba road site. This further supports the results of traditional survey techniques. As depicted in Figure 5, distinct zones are identifiable within the ECa map derived from the 10 m interval survey; these zones which visually can be seen in the vegetation health (Figure 2) and aerial imagery are spatially identified to a further degree with the EM38 survey. Soil sampling and subsequent analysis of SWRES 482, 483 and 484 identify soil texture, clay depth and EC differences (Figure 7-9). For example, the PSA of SWRES 483 (Grey Vertosol) depicted medium to medium heavy clays down to 1.1 m before a texture change to loamy sand. The EC analysis mirrors the change in texture depicted by the PSA. For SWRES 484 the texture remained relatively uniform down the profile, while the EC analysis depicted a increasing high values to 1.5 m.

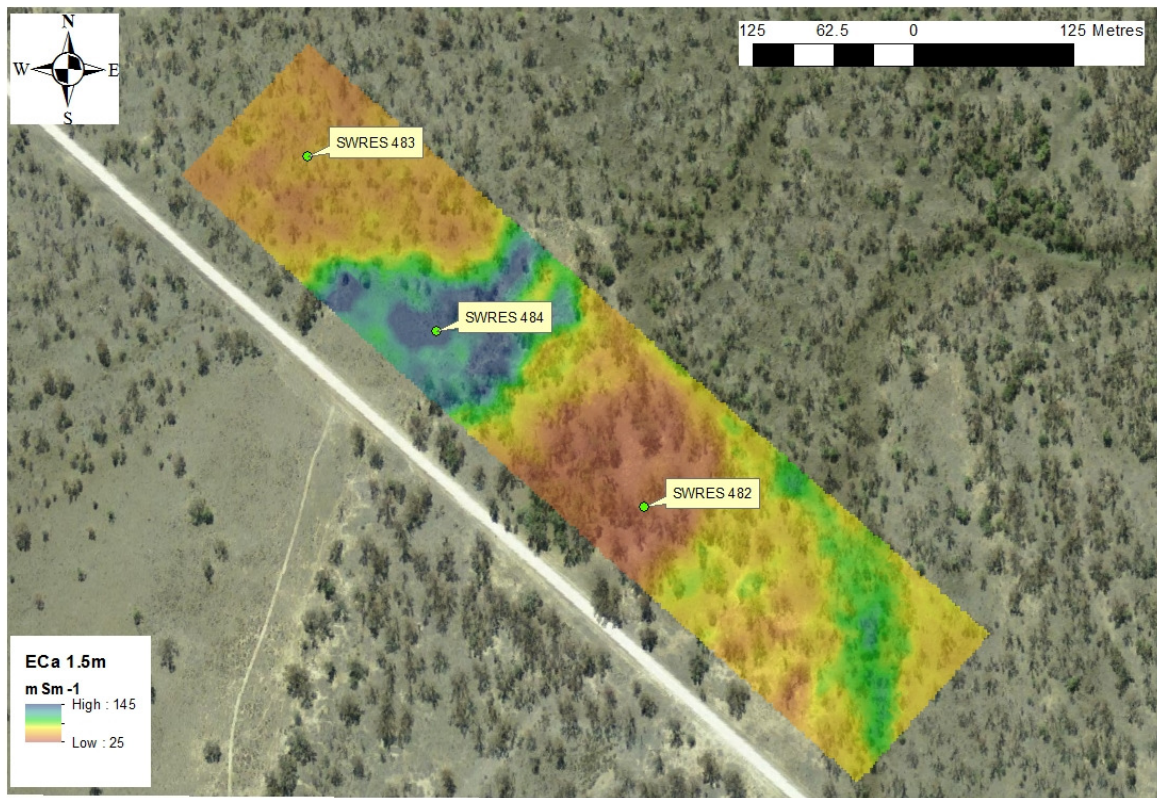


Figure 5. ECa 1.5m at Euraba road with SWRES 482, 483, 484 locations.

This information supports the derived ECa image with high values associated with areas around SWRES 484 and mid-range values associated around SWRES 483. Low ECa values are associated with low clay content and EC values around SWRES 482, the extent of the boundary can be clearly identified.

The results from the 1 m interval survey further identified microrelief and active vegetation. In Figure 6, a drainage line can be clearly identified in the north eastern portion (as shown by the dotted line). Vegetation pockets are also identifiable by the highest values within the survey (as shown by the solid line). This is supported by the presence of salts under native vegetation. In the case of the Euraba road site the EM survey supported the traditional methodology while limiting soil sampling costs.

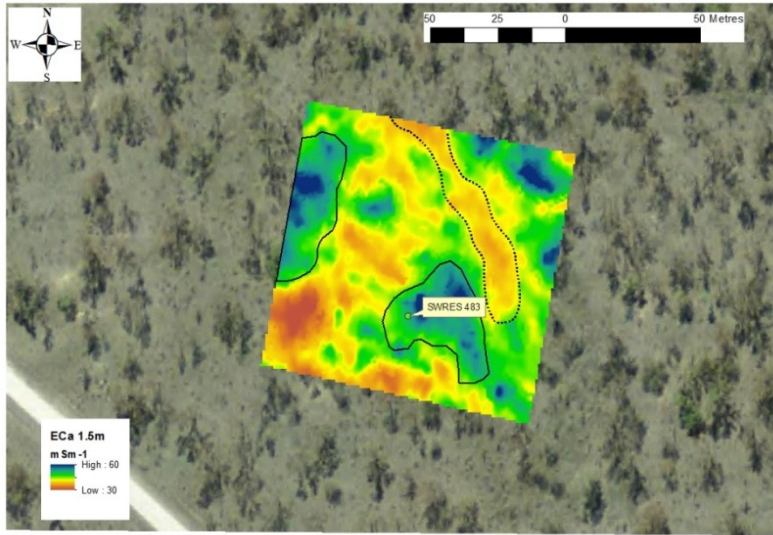


Figure 6. ECa 1.5m at Euraba road 1 m interval survey

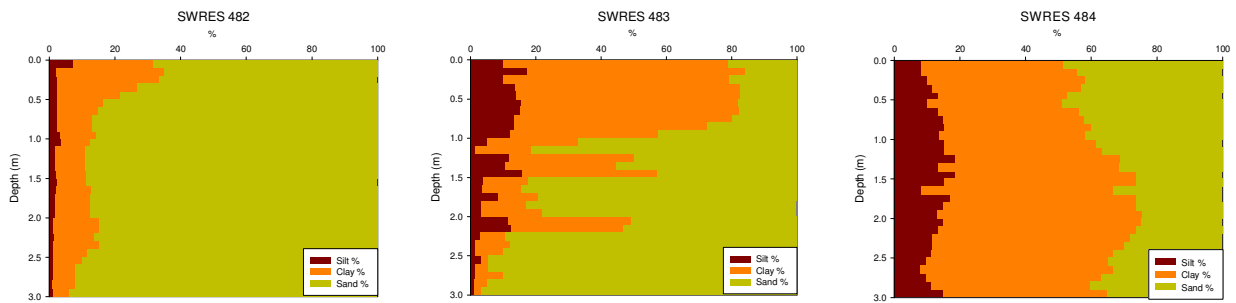


Figure 7. Particle size analysis for SWRES 482-484

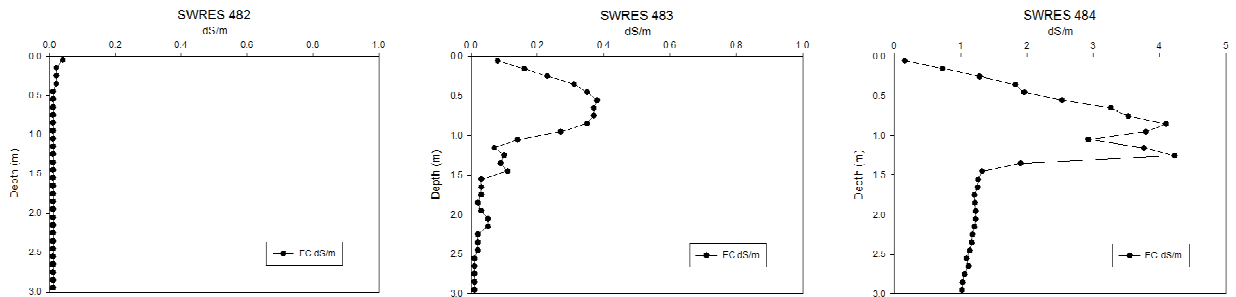


Figure 8. Electrical Conductivity (EC) dS/m for SWRES 482-484

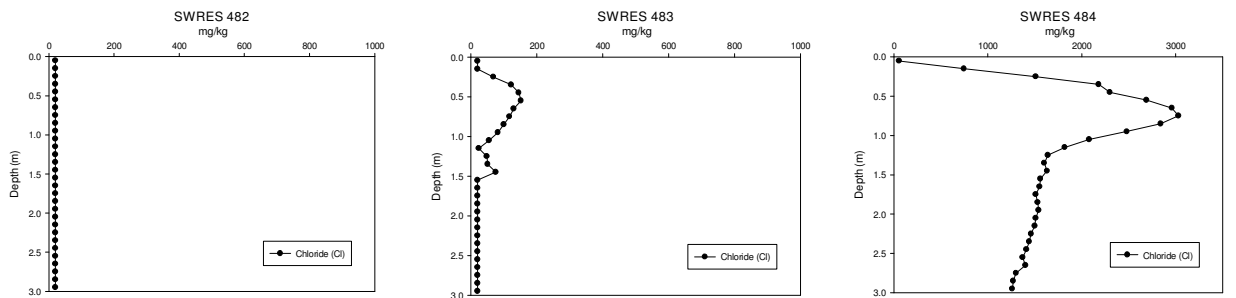
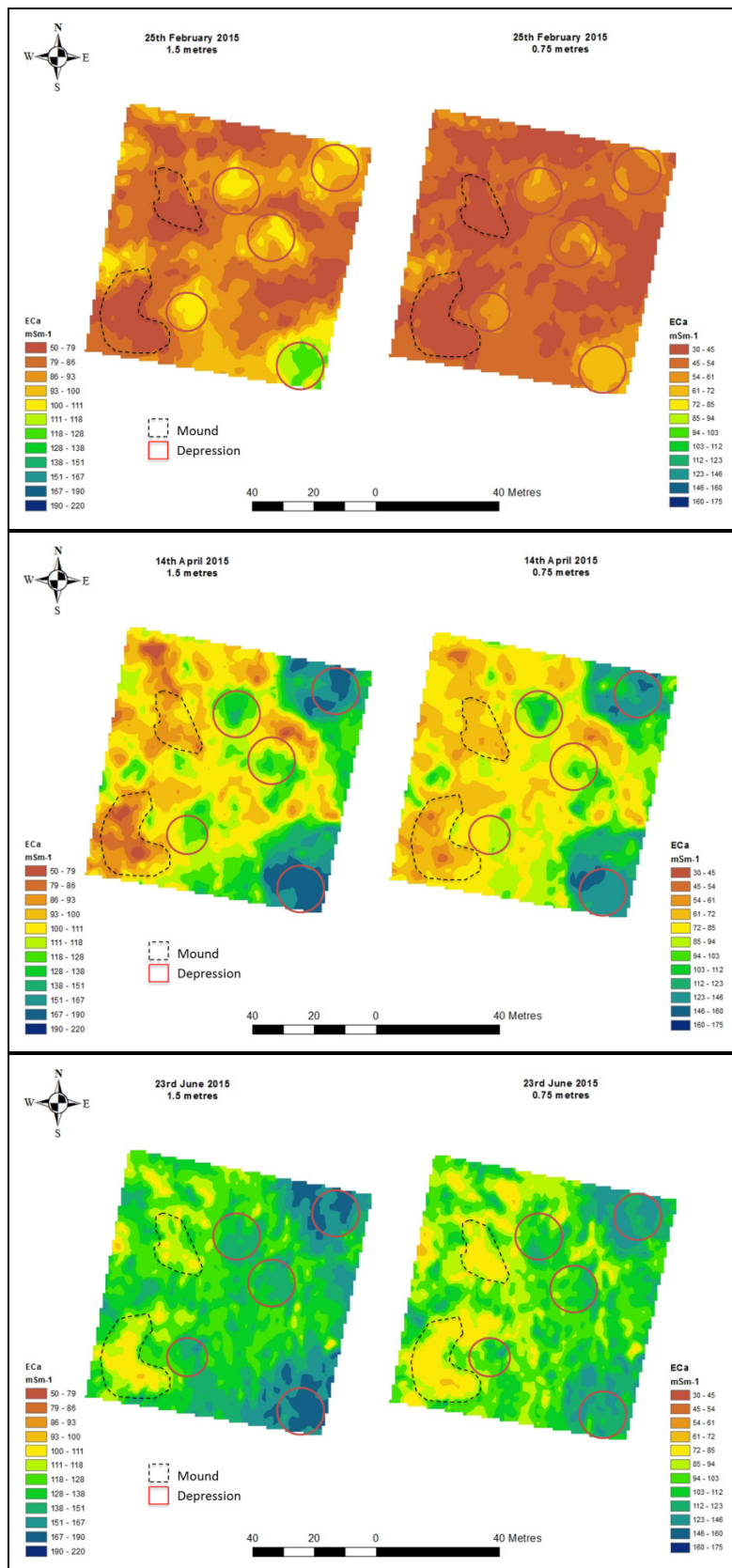


Figure 9. Chloride mg/kg for SWRES 482-484



The results from three sample dates at the Merriot road wet site demonstrated a clear pattern of mound and depression and the wetting up patterns after rainfall (Figure 10). Spatio-temporal moisture dynamics, microrelief patterns and subtle effects on water movement in the landscape caused by gilgai could be identified. The locations of depressions are clearer in the drier spectrum of the 3 surveys, while as the profile wets up after the rain the mounds become more prominent. This is to be expected as the mound will shed water at varying levels depending on the vegetation present. The early results are promising; clear patterns are emerging that identify microrelief and the potential wetting up of soil under native vegetation. As this project is ongoing the continued development of the moisture calibration curves for the multiple sites with more soil sampling and the influx of soil analysis will strengthen the story. Elevation data from terrestrial laser scans together with the vegetation analysis will be combined with the ECa derived moisture maps to gain a better understanding of the variation of water movement and soil properties.

Figure 10. ECa 1.5m at Merriot road 1 m interval survey at 3 different dates: (a) 25th February 2015, (b) 14th April 2015, (c) 23rd June 2015. The dotted lines depict mound while solid lines identify depressions.

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Rapid soil water monitoring using EM38

By Neil Huth, CSIRO Agriculture Flagship, Toowoomba, Qld.

In Brief

Total plant available soil water can be monitored quickly and easily in multiple paddocks using EM38 techniques. This allows farmers to make better decisions in situations where soil moisture is important.

Introduction

Effective monitoring of soil water is important for informing management decisions in cropping systems. Many different measurement approaches have been used depending on the type of soil and cropping system being employed. However, these can be labour intensive and so cost and logistical constraints on the number and placement of monitoring sites is always a concern for farm managers. Electromagnetic Induction (EMI) has potential advantages over other methods for soil water monitoring including speed and ease of use, no radioactive source, and its non-invasive nature. Use of the EM38 does not require wiring, electronic equipment or access tubes to be installed into the field. For these reasons, an EMI technique has been developed to enable managers to repeatedly monitor a large number of sites over an extended period in cropped fields. Our team in Toowoomba has been using EMI for soil water monitoring in scientific trials for over 10 years and some collaborating agronomists have been evaluating it for several seasons.

EMI provides a measure of the soil electrical conductivity of the soil profile, which is affected by variation in salt, clay content, organic matter, temperature, and soil moisture. Huth and Poulton (2007) showed that through careful selection of sites, and consistent reading of the same sites, the impacts of spatial variation of clay, salt and organic matter upon conductivity measures could be avoided. Furthermore, published tables help to account for any seasonal variation in soil temperatures. The remaining variation in EMI measurements correlates strongly with variation in soil moisture. This provides a rapid method for estimating soil moisture content at a large number of field locations. The following describes how such EMI techniques can be employed for soil water monitoring for informing crop management.

The EM methodology

The EM38 (Geonics Ltd, Canada, Figure 1) measures the apparent bulk soil electrical conductivity (ECa) by inducing a small current within the soil via a primary electromagnetic field from a transmitting coil and measuring the resultant secondary field back from the soil via a receiving coil. The EM38 allows two depth responses through simple changes in the orientation of the instrument (vertical, horizontal). The depth response for the vertical dipole is much deeper than for the horizontal dipole (Figure 2) which is heavily influenced by surface EC.



Figure 1. EM38-MkII in the field. The unit is sitting in the vertical dipole position. Horizontal dipole is obtained by placing the unit on its side.

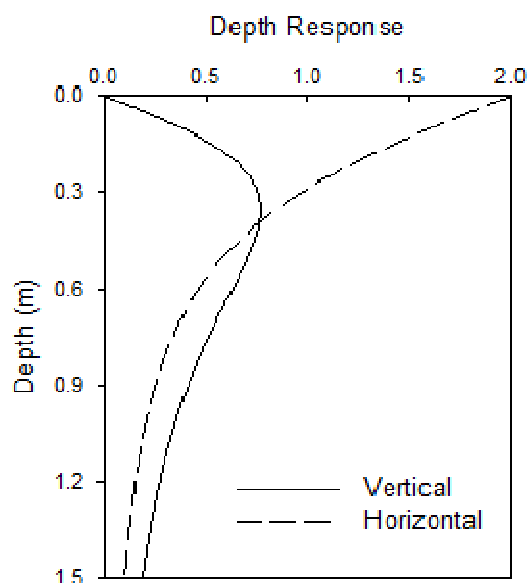


Figure 2. Depth response functions for EM38 used in either the vertical or horizontal dipole.

The approach to applying the EM38 for soil water monitoring is simply this:

- 1) Paired EM38 readings in the vertical (EC_v) and horizontal dipoles (EC_h) are taken at chosen representative sites in a field. Consistent monitoring of the same sites minimises the impact of spatial variation in soil salts, clay and organic matter, which can affect EC_a readings.
- 2) Each EC_v and EC_h reading is corrected for seasonal temperature variations using published tables of temperature correction factors from Huth and Poulton (2007).
- 3) A combined total EC (EC_t) is calculated from the temperature corrected values using the equation $EC_t = 0.77 * EC_v + 0.23 * EC_h$. This combines the two signals into a value that represents a measurement that is more evenly distributed with depth.
- 4) EC_t can then be used as a measure of total soil water by comparing to wet and dry readings to provide a field-specific calibration for the EMI soil water monitoring technique.

Previous studies have shown that values of EC_t obtained in this way correlate closely with soil water accumulated to depths of 90cm or deeper. Figure 3 shows data for a field near Warra, Qld where EC_t was used to estimate soil water to a depth of 90cm. This data includes soil profiles that were close to the crop lower limit (i.e. 0 mm Plant available water (PAW)) or at drained upper limit (i.e. 153 mm PAW to 90cm in this soil). A linear fit to the data explains 93% of the variation (Figure 4).

Experience shows that good estimates of EC_t for wet and dry soil profiles alone provide a good reference for ongoing monitoring of soil water using EM38. For example, if the dry and wet readings were known from previous monitoring on the site, the relative value of any EM38 reading between these two extremes can be used to estimate the fractional PAW for the field (e.g. 50% full). In Figures 3 and 4, a profile that is half full is shown in both cases.

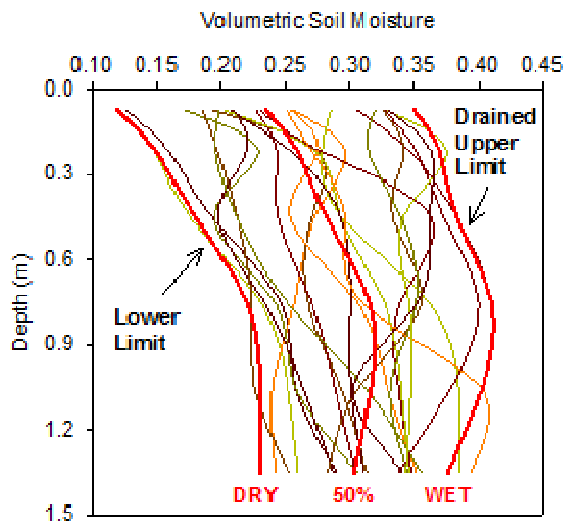


Figure 3. Soil water profiles used in the calibration of the EM38. Dry readings correspond to crop lower limit. Wet readings correspond to drained upper limit.

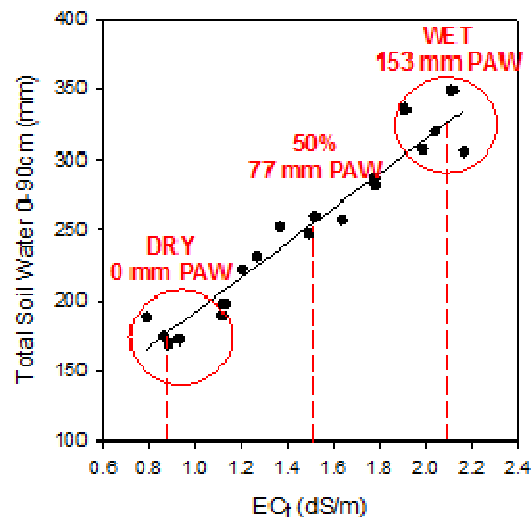


Figure 4. Plot of Total Soil Water to 90mm versus EC_t . Note linear relationship between soil water and EC_t . If wet and dry readings are known, fraction of plant available water can be calculated very easily

Techniques such as these have been used by the CSIRO Toowoomba team for over a decade now for the rapid monitoring of soil water in trials where a large number of measurements are required. For example, Figure 5 shows estimates of total soil water to 90 cm for a deep black vertosol at Nangwee, Qld in 2013. This trial included three times of sowing. The first time of sowing had some restrictions on early growth and the second sowing ultimately yielded higher. Note that the EM38 readings were able to show that water use from the second sowing caught up to, and then exceeded, the first sowing.

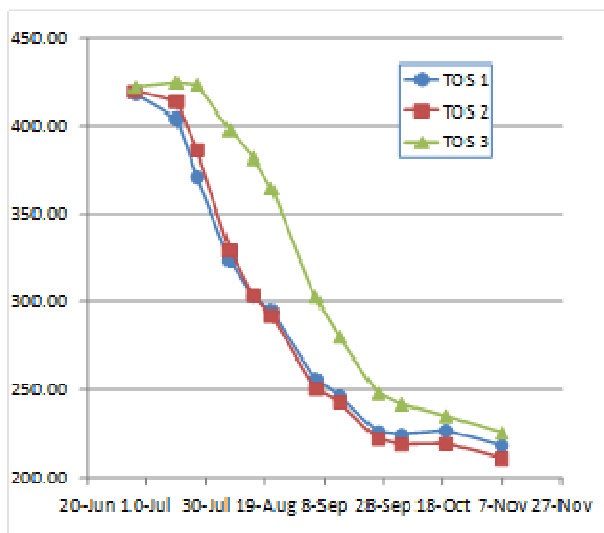


Figure 5. Time course of estimated total soil water to 90cm depth using EM38 for three times of sowing for wheat at Nangwee, Qld in 2013.

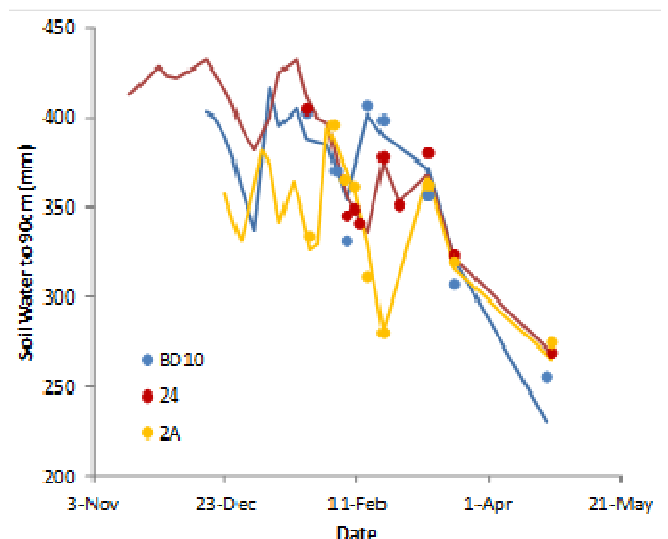


Figure 6. Time course of estimated total soil water to 90cm depth using NMM (lines) and EMI (symbols) for irrigated cotton fields near Brookstead, Qld.

Soil water monitoring using EM38 is also being trialled by agronomists in SE Queensland. Here, irrigation of cotton is often managed using soil water information monitored using neutron moisture

meters. However, logistical considerations heavily influence the extent of the use of neutron probes. Side-by-side comparison (Huth et al, 2012) of EM38 with neutron probes have shown that the EM38 is able to explain well over 90% of the variation in soil water measured with probes, but without the need for access tubes or radioactive sources, and with a much smaller time requirement.

What can I do with this information?

Information regarding your current soil water status can be useful in a range of crop management decisions. These could include the following scenarios:

- 1) To grow 3t/ha of sorghum I need 300mm of PAW + rainfall. How much of this is already available in the soil? How much of this will I need from rainfall?
- 2) The Bureau of Meteorology is predicting a very dry summer. If I know my stored soil water I can estimate a minimum likely yield. Is this yield enough to be worth the risk?
- 3) The forecast is for a good season and I have good stored moisture. I can use these to predict potential yield. What other management do I need to consider for reaching these yield levels?

Pros versus Cons

If you choose to use EM38 you will need to weigh up the pros and cons for this instrument versus other approaches available in the market.

Pros	Cons
Very Portable - nothing remains in field	High up-front capital expenditure (~20k)
Rapid – so can take more measures from more locations	Point in time measurement – you cannot have it logging continuously. This may not be an issue.
Large zone of measurement – some sensors only sense a small volume of soil	Requires calibration for each soil type – as is the case for all probes
Non-destructive	Affected by high salt and salt variability
Relatively simple to calibrate	No detailed layered soil information
Low ongoing operating costs	
Similar accuracy to neutron moisture probes	

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Acknowledgements

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Presented at the Burren Junction GRDC Grains Update July 2014 by Neil Huth

<http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/07/Rapid-soil-water-monitoring-using-EM38>

Diagnosing traffic based soil compaction with an EM38

By John McL. Bennett, J. Lei and L. de Vetten, NCEA, USQ, Toowoomba

Introduction

Soil compaction is a worldwide issue for agricultural production (Soane & van Ouwerkerk 1995) and is considered the utmost impact of modern agriculture on the environment (McGarry 2003). Controlled traffic farming techniques – where all machine traffic is constrained to permanent tracks (tramlines), machines and implements operate on inline wheels (i.e. no requirement for dual wheel configurations) and these wheels are at a matched width between wheels on an axle – are proven to reduce this impact (see Tullberg, Yule & McGarry 2007). However, such systems have been slow to be adopted, with many landholders indicating that they can't see compaction and its effect, so it is a forgotten issue most often. This highlights the importance of providing a graphic representation of impact and being able to produce this at low cost and high resolution of farm coverage.

The use of electromagnetic induction (EMI) survey technique provides the required resolution and can be undertaken relatively rapidly, resulting in reasonable cost. Numerous studies have indicated that EM38 sensors (EMI technology) are capable of detecting increases in soil density due to anthropogenic intervention (soil compaction). However, while previous investigations using an EM38 to determine soil compaction have shown merit, they have in majority focused on highly contrasting densities such as existing plough-pans (subsoil compaction) (Hoefer & Bachmann 2012) or imposed low density zones in maximum dry density clay liners (Guyonnet et al. 2003). Additionally, the majority of studies have occurred in coarse textured soil at low moisture content.

These studies use the standard Geonics EM38 with a 1.0 m transmitter and receiver spacing, allowing a 1.5 m and 0.75 m depth of interrogation in the horizontal and vertical mode of EM38 operation. Given the integrated nature of ECa measurement (see “Theoretical concept” section), dilution of compaction effect in the EM38 response at either horizontal or vertical dipole configuration is likely to have occurred, which could also have affected the ability to detect changes in soil compaction. However, Geonics newer EM38-MK2 includes two receiver coils spaced at 1.0 and 0.5 m from the transmitter, providing data from effective depth ranges of 1.5 m and 0.75 m respectively (vertical dipole orientation), and 0.75 m and 0.375 m respectively (horizontal dipole orientation). Hence, our study sought to investigate the ability of an EM38-MK2 to diagnose traffic based soil compaction at a range of soil moisture contents, with relatively low density contrast, and in high clay content Australian Vertosol soils.

Theoretical concept

The electromagnetic induction (EMI) survey technique induces alternating currents within the soil that are linearly related to the soil electrical conductivity (EC) using a varying magnetic field (McNeill 1980). The below-ground response is then analysed to determine electromagnetic fields and the ramification of differences depending on the depth response of the instrument. EMI instruments use a transmitting and receiving coil to interrogate electromagnetic field response, whereby the transmitting coil is excited using sinusoidal current, creating a time-varying magnetic field that induces eddy currents (secondary magnetic field within the primary magnetic field) within the soil (Lamb, Mitchell & Hyde 2005). It is the magnitude of these eddy currents that is proportional to soil

EC, and the receiver intercepts a fraction of these which are returned as an amplified summation in the form of an output voltage.

While this method is considered a measure of EC, it is actually measuring the apparent EC (EC_a) which is the EC integrated throughout the depth of measurement; a depth weighted EC according to the theoretical respective depth response functions (McNeill 1980). Hence, at any single point of measurement, the EC_a returned by the instrument is an integration value determined by both the depth related sensitivity and the predominant, depth dependent, drivers of the soil EC (Hossain et al. 2010; Sudduth, Drummond & Kitchen 2001). Considering this, the EM38 MKII provides four maximum depth weighted responses over which to assess soil electrical conductance, with the data from the smallest depth included in the depth weighted integrations of greater depth assessments.

As explained by Roades et al. (1989), and depicted in Figure 1, the current flows through three pathways: 1) a liquid phase pathway (soil pore water and its salt content); 2) a liquid-solid phase pathway; and, 3) a solid pathway (direct, continuous contact between soil separates). However, the soil matrix does not usually provide sufficient direct, continuous contact between soil separates for continuous current flow.

The EC of a soil is governed by multiple soil properties (McKenzie et al. 2008), predominantly: 1) Pore network characteristics (primarily defined by clay content and type) and connectivity; 2) Water content with depth; 3) Concentration of dissolved salts in the soil water; and, 4) Temperature and phase of the pore water (phase referring to frozen/unfrozen). Hence, soil bulk density (and compaction) is considered to affect EC_a measurement (Corwin & Lesch 2003, 2005; Hossain et al. 2010).

When considering a given volume (V), where a soil is compacted into that volume, more soil solids are contained in V, than for the same soil when not compacted. The volume of soil (V) is described by:

$$V=V_S+V_A+V_w$$

where V_S is the volume of solids, V_A is the volume of air, V_w is the volume of water, and V_A+V_w is the soil pore volume. Thus, if V is to remain constant, as per the consideration, as V_S increases V_A+V_w must decrease. Additionally, if soil pore space is decreasing, the diameter (d) of the soil pores must be decreasing also. This is important because as soil pore diameter decreases the suctions required to remove water from a pore increases (i.e. more work must be done to remove water).

In considering how compaction would be expected to affect electrical conductivity, we can use Figure 1. The likelihood of pathway 3 being responsible for conductance is increased. Where gravimetric moisture content (mass of water per mass of soil) and soil solute concentration are not changed, we would expect the volumetric water content (volume of water per volume of soil) to be increased if the soil is not moisture saturated. Thus, we would expect an increase in soil conductivity due to the volumetric moisture and soil solid contact increases. Where a crop is included in the scenario, we might expect the compacted zone to exhibit further contrast in terms of high EC due to the effect of increased suction (plants must work harder to access water from the compacted zone).

Pathways of Electrical Conductance Soil Cross Section

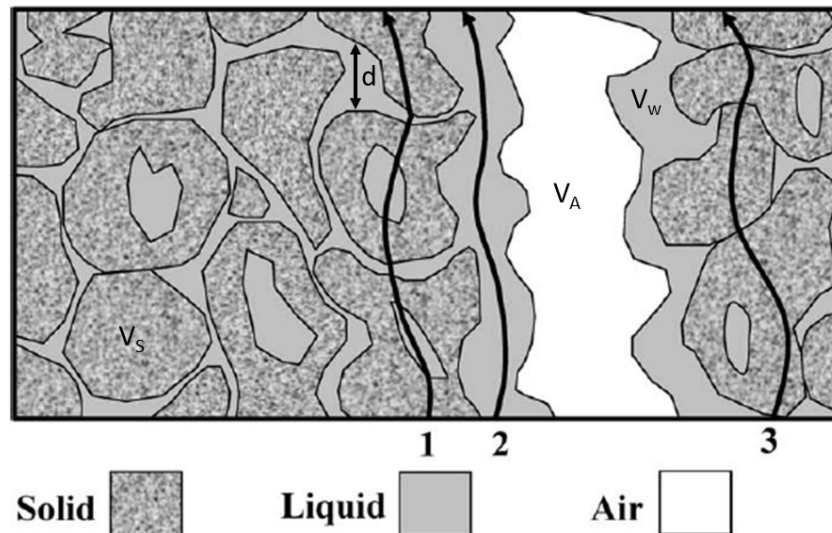


Figure 1. Conductance pathways; d , is pore diameter, V is volume and W , S and A refer to water, solid and air, respectively (modified from Corwin and Lesch 2005)

Methods

Vertosol soils were used in the investigation. Investigations were carried out on 1) a long term controlled traffic paddock and 2) on a paddock never subject to traffic. Investigation 1, like the numerous previous studies, allowed a stark contrast in bulk density between traffic lanes and un-trafficked field. Unlike previous studies, this also allowed a high clay content soil at numerous soil moistures to be investigated over time. This site was located near Jimbour, Queensland. Two sub-sites were used in this location, whereby the first had recently come out of crop, and was thus drier than the second, which had been in fallow. This allowed greater assessment of the moisture range. The sub-sites were located within 400 m of one another.

Investigation 2 was conducted to assess the capability of the EM38 MKII to detect soil compaction of a single pass of a standard, dual wheel front axle John Deere 7760 cotton picker. EM38 assessment was undertaken by hand prior and post traffic to assess natural variation.

For both investigations, soil bulk density was determined every 10 cm to a depth of 80 cm. These samples were also used to determine soil moisture content. Soil strength was assessed using a constant insertion velocity cone penetrometer. Whilst this device is strongly influenced by soil moisture, measurements were taken directly before and after traffic, so relative differences indicate differences in soil strength due to soil compaction. These data are not shown in this article for brevity.

Results and discussion

Investigation 1

The fieldwork undertaken for investigation 1 resulted in 40 ECa response maps: 2 different sites x 4 different positions x 5 different measurement timings. The response maps for the V0.5 position (0.75

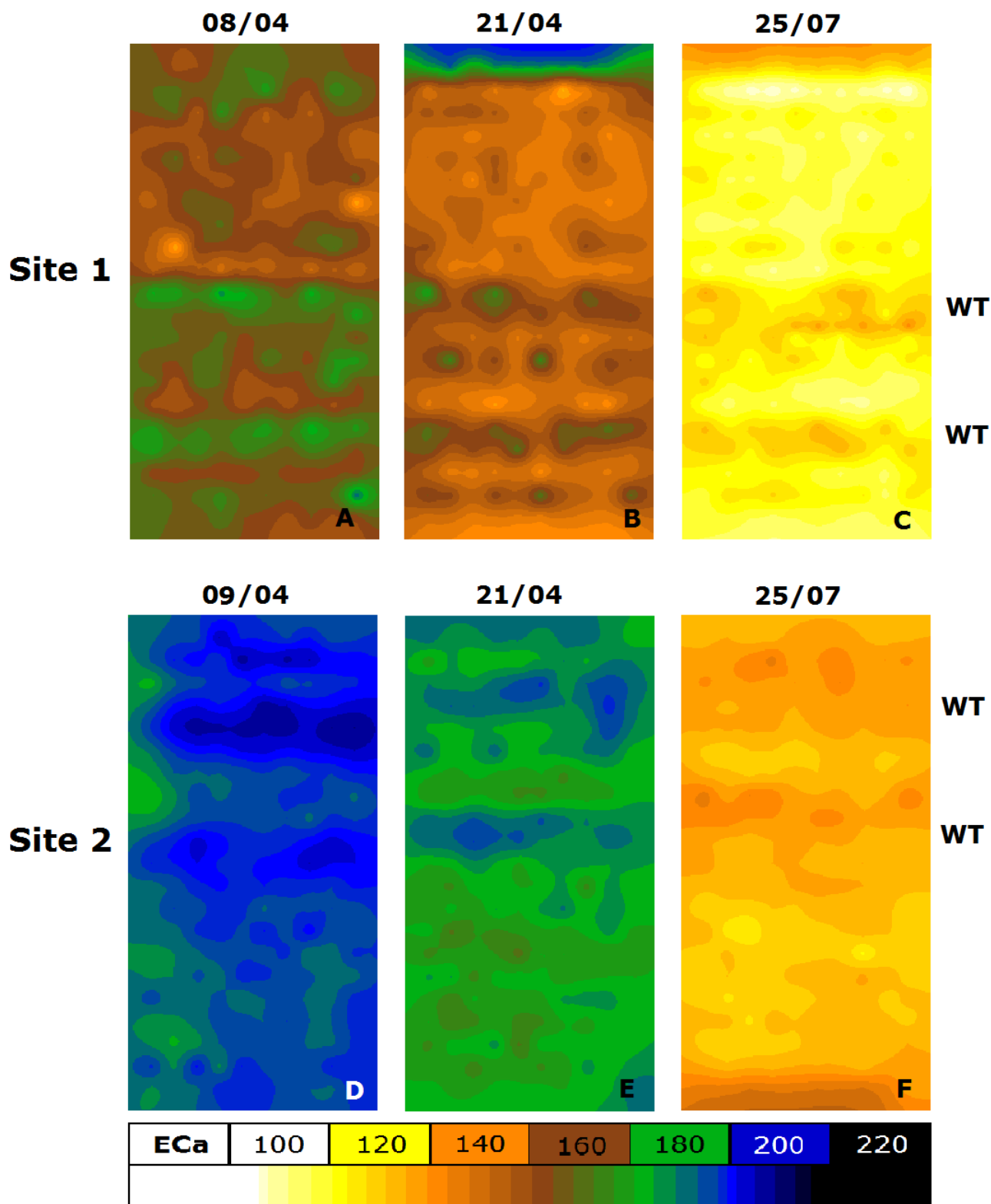


Figure 2: Maps of ECa (mS/m) as measured by the EM38 in the V0.5 position. Numbers above each map indicate date of measurement. Assessment occurred in the year 2014

m depth) for the first three measurement timings are presented in Figure 2. It is observed that over time as the soil dried out, lower ECa values were measured, reflecting the importance of soil moisture as a factor influencing ECa. Within the maps linear horizontal features with higher ECa values can be distinguished, correlating to the wheel tracks (WT) as observed on the surface. Noteworthy, between map A and B there was a single pass from agricultural traffic (spray rig), resulting in a clear feature at the top of maps B and C. Similarly, a linear feature is found at the bottom of map F at site 2. This highlights the effect of a single traffic pass, even on soil zones subject to high traffic loads, and indicates the volumetric moisture content effect discussed in the theoretical concept section.

The average gravimetric soil moisture content for the 0.75 m depth was 32, 29, 22, 38, 34, and 27% for A, B, C, D, E and F, respectively. The bulk density for the traffic lanes was 1.59, while it was 1.24 for the non-traffic zones, on average over depth and sites. This bulk density was obtained from soil near field capacity. Vertosol soils have shrink-well characteristics that affect bulk density with soil moisture, which is likely to affect EC as well, but is not considered here. Thus, it can be seen that the EM38 MKII is capable of diagnosing high contrast soil compaction at a large range of soil moisture contents in soils with high clay content.

It was also noted that high EC was strongly correlated with bulk density and moisture corrected soil strength (data not shown). Furthermore, the linear features representing soil compaction from wheel tracks (high EC) were more pronounced in the Horizontal 0.5 m configuration, but are not shown here; the Vertical 0.5 m configuration is shown instead to provide a similar depth of investigation to previous studies.

Investigation 2

A summary of results for investigation 2 is shown in Table 1. In this case, interpolated response maps have not been used to depict results in order to statistically and simply show the compaction effects. Between traffic and non-traffic furrows it can be seen that there is a significant increase in ECa where traffic has occurred for V0.5, H1.0 and H0.5 instrument configurations. This indicates that the EM38 MKII has been able to diagnose compaction due to wheeled traffic. The results are different for the H1.0 and V0.5, which can be attributed to the depth weighted integration for vertical and horizontal configurations (this being different with weight placed slightly deeper in the horizontal mode).

This data further shows that the difference in ECa is more substantial where the interrogation depth is shallower, which is as to be expected considering the stress load effect is greatest at the soil surface. Such a result confirms the issue of impact dilution as the depth of interrogation is increased.

The compacted bulk density for 0–38 cm and 0–75 cm was 1.52 and 1.56, respectively, whilst for non-traffic furrows it was 1.41 and 1.50, respectively. Hence, the EM38 MKII was capable of diagnosing less contrasting compaction effect. These data were again strongly correlated with soil bulk density and soil strength (data not shown).

Table 1. Apparent electrical conductivity for the four interrogation depth configurations of the EM38 MKII. Numbers in the same column followed by different lowercase letters indicate significant differences at $p < 0.05$. Traffic furrows include data from all four machine tracks, differential furrow refers to the untrafficked furrow beneath the centre of the machine, whilst the guess furrow is the furrow not trafficked, but between two machine frontages.

Furrow	EM38 configuration			
	V1.0 1.50 m	V0.5 0.75 m	H1.0 0.75 m	H0.5 0.38 m
Traffic	113.0	89.0a	79.3a	61.3a
Differential	117.7	85.7b	70.3b	51.3b
Guess	116.7	84.3b	69.3b	48.7b

Conclusion

Use of an EM38 to diagnose compaction has merit and should provide a more cost effective way by which to demonstrate graphically the effect of machine traffic on the soil resource. The Geonics EM38 MKII has proven capable of diagnosing soil compaction in high clay content soils at a moisture range of 38–22% gravimetric soil moisture.

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Identifying a non-destructive technique to assess nematode tolerance in wheat variety trials.

By *Jeremy Wish¹, John Thompson², Tim Clewett² and John Lawrence¹*

¹ CSIRO Ecosystem Sciences/APSRU, 203 Tor St Toowoomba 4350, Email Jeremy.Wish@CSIRO.AU

² Queensland Department of Employment, Economic Development and Innovation, Leslie Research Centre PO Box 2282, Toowoomba Qld 4350.

Abstract

Wheat cultivars and breeding lines are rigorously tested to identify their level of tolerance to nematodes under field and controlled environment conditions. Unfortunately field-testing can often be compromised by poor seasons or inclement weather resulting in incomplete or lost data.

Root-lesion nematodes (*Pratylenchus thornei*) decrease root function resulting in reduced uptake of water and nitrogen from the soil and in turn results in poor canopy development. This plant damage as a result of the nematode population can be measured by the use of electro magnetic induction (EM38) for soil water estimations and ceptometry for canopy cover analysis. These tools offer the potential to non-destructively compare different wheat plots growing on soils with known high population of nematodes, thus providing an in-season comparison between varieties.

This technique was used to assess four wheat varieties that ranged in nematode tolerance from intolerant to tolerant. The EM 38 identified the four varieties as having significantly different water use, ten weeks after sowing. The ceptometer identified the most intolerant varieties before symptoms were easily visible to an observer. The combined use of ceptometry and EM38 found differences between the tolerant and intolerant varieties that normally would require final yield comparison.

In the coming years this early screening method will be tested across the cohort of varieties used in the national variety testing program (NVT). This simple non-destructive method of screening varieties will provide additional quantifiable information and reduce the reliance on final yield data.

Introduction

Root-lesion nematode (*Pratylenchus thornei*) is a common pathogen found in the Australian wheatbelt and causes significant damage to wheat crops grown in northern NSW and southern Queensland. The lost production as a result of *P. thornei* damage is estimated to be \$38 million per annum (Murray & Brennan, 2009). Wheat plants infected by *P. thornei* suffer reduced root function, limiting the supply of water and nutrients to the plant. This restriction on supply results in poor plant growth with wheat plants appearing stunted, with chlorotic leaves, reduced tillering and poor yield (Thompson et al. 1995). This poor growth has been reflected in water uptake measurements with intolerant wheat using less water than barley in long term rotation trials (Thompson et al., 1995).

These symptoms of nematode damage, combined with final yields are used to rank wheat varieties for nematode tolerance in breeding trials. This qualitative method of in crop ranking is dependent on the skill and knowledge of the observer and the quantitative final yield measurement. Measuring plant water use and leaf area is one way to quantitatively identify differences in plant growth (demand) and plant available water (supply) during the season. Historically, the monitoring of leaf area and soil moisture have been destructive, time consuming or required permanent installation of

sensors; however, the development of portable lightweight photosynthetically active radiation (PAR) sensors and recent work on the use of electro magnetic induction (EM38) for soil moisture monitoring (Huth & Poulton, 2007) has simplified these measurements.

This paper describes an experiment that tested if EM38 measurements combined with leaf area measurements using a ceptometer, have sufficient precision to identify differences in water use and leaf growth, of wheat varieties with a range of tolerances to nematodes.

Methods

This work examined a sub set of varieties that were part of the national wheat variety-testing program. Wheat varieties were sown (25/6/2011) on a site with a managed high population of nematodes in a completely randomised block configuration. The sub-set of varieties monitored were selected for their varying susceptibility to nematodes and ranged from susceptible (Strzelecki) to the tolerant and partially resistant breeding line (QT8447). The final two varieties (EGA Wylie, and Kennedy) are positioned on the tolerant side of the scale. Kennedy was sown on both high and low initial-nematode populations (Kennedy H and Kennedy L).

Soil water was measured non-destructively during the season using a hand held EM38. Measurements were collected from the vertical and horizontal dipoles at two places within the inter-row space, of the centre rows in each plot. The two readings were temperature corrected and converted to a single $E_{c_{tot}}$ reading following the method described by Huth & Poulton (2007). The $E_{c_{tot}}$ values were converted to mm of water from the 0 to 120mm depths via a calibration curve developed from destructive sampling of the buffer strips. To ensure a range of moisture contents the buffers were strategically sampled during the season.

Leaf area index was calculated non-destructively with an AccuPAR LP-80 Ceptometer (Decagon Devices, Inc). The crop rows were sown in a north south direction and the ceptometer was inserted below the canopy, across the centre 3 rows, at a slight angle to ensure both ends of the sensor rod were in the centre of the first and third crop row. Eight below-canopy and four above-canopy readings were collected in each plot and integrated to calculate a leaf area index (LAI) using the default values for wheat. All readings were collected during the middle of the day between the hours of 10 am and 3 pm.

Statistical analysis was undertaken using the statistical software package R (Team, 2010).

Results and Discussion

EM38 and LP-80 ceptometer readings recorded on the 4/10/2011 showed significant differences ($P \leq 5\%$) between the susceptible variety Strzelecki and the tolerant varieties. The reduced water use and corresponding limited leaf area measured in the Strzelecki plots contrasts with the higher water use and larger leaf area observed in the partially resistant line (QT8447; Figure 1). The tolerant varieties had similar water use to QT8447 but did not produce the same quantities of biomass. On going measurements of LAI maintained this pattern with the tolerant species extracting similar amounts of water as QT8447, but producing less leaf area. We hypothesise that this is an indication of the tolerance mechanisms in these species. Such mechanisms would include continually producing new roots to depth to replace those damaged by nematodes instead of growing more leaves.

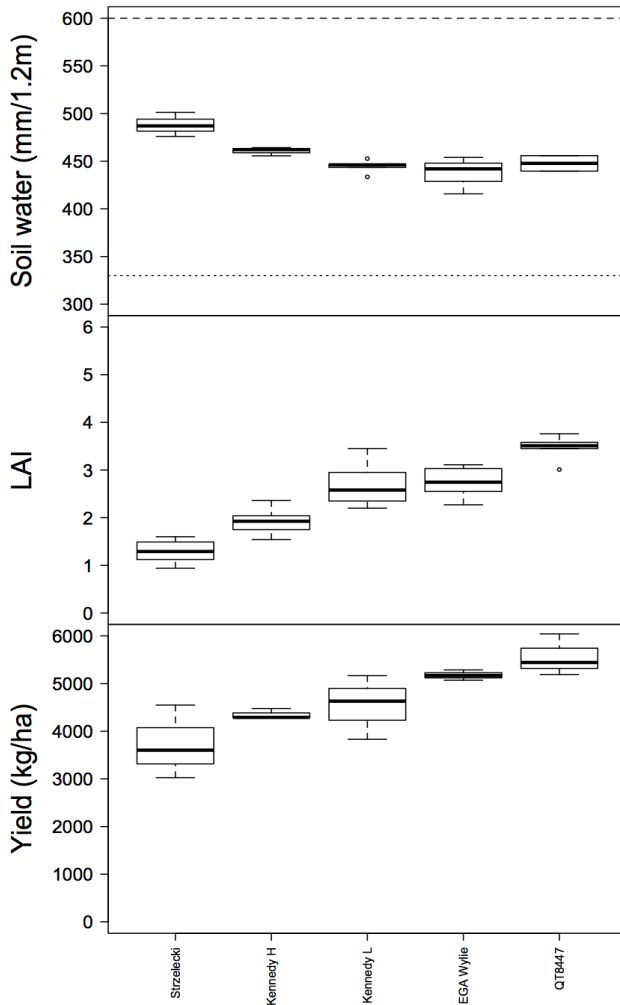


Figure 1. Boxplots showing available soil water, LAI and final grain yield for each wheat variety. Soil water and LAI were measured by the EM38, and LP-80 ceptometer on 4/10/2011, the average wheat developmental stage at this time was Z47, flag leaf sheath opening, (Zadoks et al., 1974). The nematode susceptible variety Strzelecki had used the least water, produced the smallest leaf area and by harvest (23/11/11) had the lowest grain yield. Dotted lines on the soil water figure indicate drained upper limit (DUL) and crop lower limit (LLwheat).

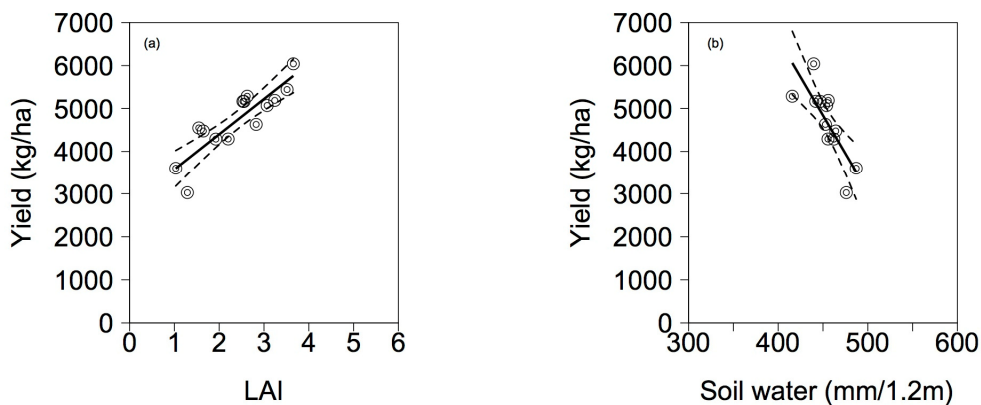


Figure 2. Regressions of LAI (a) and soil water (b) at Z47, (flag leaf sheath opening; (Zadoks et al., 1974) against final yield showing a strong predictive relationship ($R^2 = 0.76$ for LAI and 0.62 for soil water) between the non-destructive measurements and final grain yield.

Soil water measurements and leaf area measurements recorded in early October correlated well with the final grain yields recorded 7 weeks later (Figure 2). This correlation highlights the value of these non-destructive measurements in providing quantitative data on the tolerance of different wheat cultivars to high populations of nematodes and providing an indication of the mechanisms with which these pathogens reduce wheat grain yields.

Conclusions

The results from this preliminary study show the non-destructive measurement of soil water and leaf area could distinguish differences between the varieties before flowering. The varieties selected for this study covered a range of tolerances to *P.thornei* future work will examine the whole national variety testing suite to see where each variety lies on this continuum, and how the soil water within each plot and leaf area readings relate to final yields.

The use of these non-destructive techniques on existing breeding plots has significantly enriched the data collected beyond current practice. Current practices rely on qualitative assessments and grain yields to rank each cultivars' level of tolerance. These methods are well tested and reliable, however, their quantitative nature provides little insight into the mechanisms or timings of the damage caused by the nematodes. The use of EM38 to estimate soil water combined with a ceptometer to measure leaf area, allows monitoring of both the supply and demand terms for plant growth. Regular use of these tools will identify the individual tolerance point for each variety. That is, the point where growth by intolerant and tolerant varieties differs. Over time the collection of this data combined with meteorological data, and pathogen population numbers will improve our knowledge of how pathogens, crops and the environment interact to set final yield.

The strong relationship between leaf area and water use measured before flowering and grain yield, offers some protection if inclement weather conditions prevent final harvest or damage before harvest can be completed. The relationship observed in this study was strong, despite the season being particularly wet with above average in-crop rainfall. Below average rainfall or a more variable season would increase stress and may accentuate the differences between the intolerant, tolerant and resistant varieties.

The work presented in this paper is preliminary, over the coming season the techniques described will be applied to NVT nematode trials at different sites and at different sowing dates to further assess the technique.

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Proceedings of the 16th ASA Conference, 14-18 October 2012, Armidale, Australia. Web site www.agronomy.org.au

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Using EM 38 for detailed study of soil water in wheat

By Brett Cocks and Neil Huth, CSIRO Agriculture Flagship, Toowoomba.

Experiences in using EM 38 to measure soil water in a multi variety replicated wheat trial



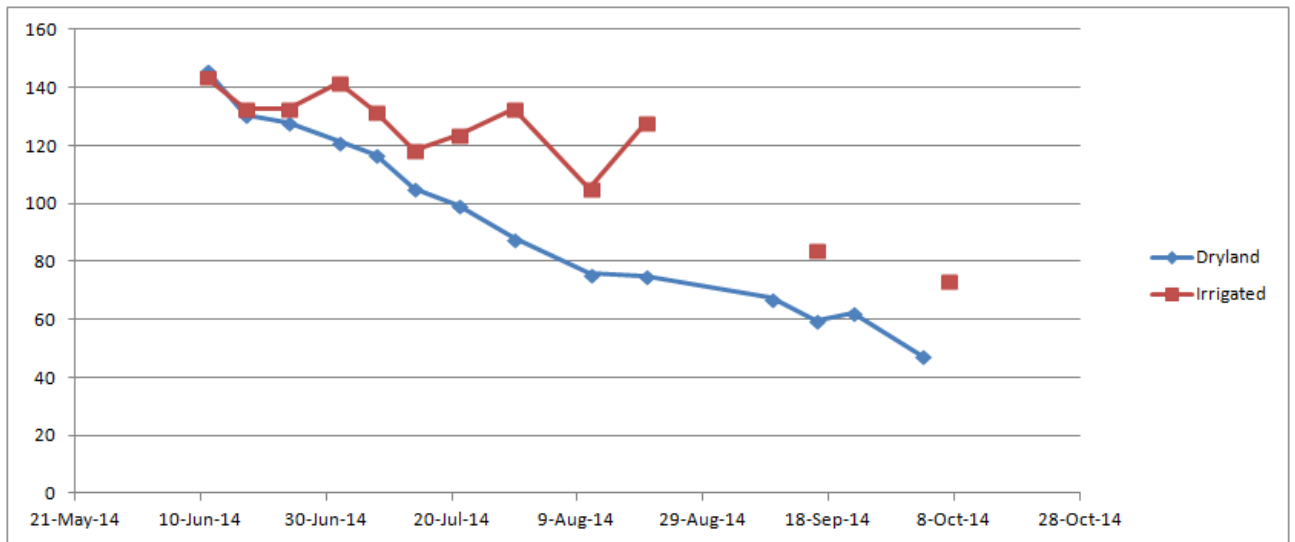
During the growing season of 2014 we ran a wheat trial consisting of 12 varieties replicated four times with both an irrigated and dryland treatments.

To assess the variation between the irrigated and dryland plots and also between varieties we needed to have at least weekly soil water measurements. Due to constraints with time, labour and available land we decided to use weekly EM38 measurements as a surrogate for soil water. This allowed us to take soil water measurements at 4 locations in each of 96 plots every week.

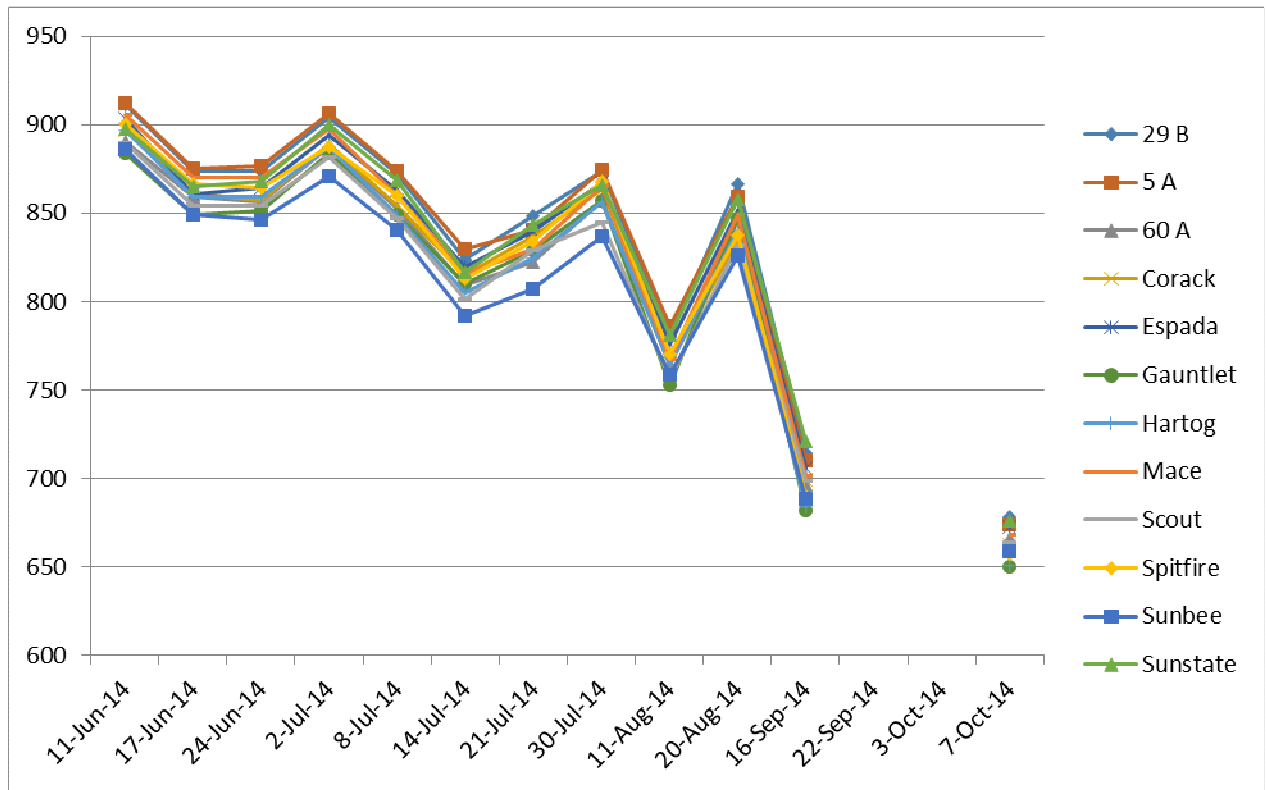


DAFF Research Station Lawes

- Consistency of soil type (clay, salt, EC)
- Calibration methods (used opportunistic soil cores throughout the season to sample across the available water range and across space)
- Sampling intensity (rapid so we chose 4 per plot)
- Data interpretation



- Variety differences



How to make a pretty picture, from start to finish using Dat38MK, Vesper and ArcGIS

By Mark Crawford – Department of Natural Resource and Mines, QLD

In Brief

This overview covers a step by step process of how to produce an ECa map after carrying out a survey; it involves the programs Dat38MK, Vesper and ArcGIS 10.2.1. It sources heavily from the manuals of each program and acts as a guide to demonstrate a possible scenario. It is recommended you read the manuals as they contain more information than this overview - or contact the provided sources.

DAT38MK

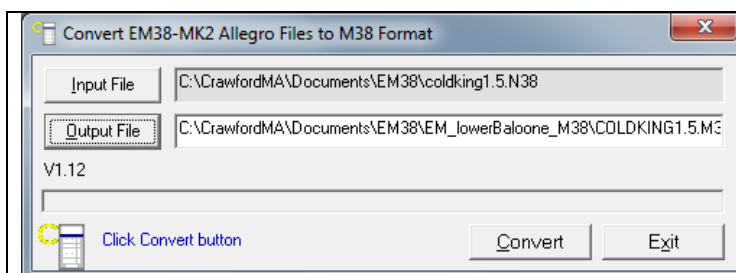
The data acquisition program EM38MK2, operating in the field computer, saves readings in a raw (binary) files format which are given the extension name N38. Once transferred to your PC these files need to be converted to M38 files.



The transfer of the N38 files to your PC was achieved using Windows Mobile Device Centre. Example folder name for the data could be Dat38MK_Raw or Dat38MK_N38. Transfer of raw files from the Allegro CX field computer to desktop PC can also be performed with MS ActiveSync or by PC memory card.

Figure 1. Windows Mobile Device Centre

DAT38MK2 uses the ASCII format of data files so once the data has been transferred, open Dat38MK2 and click the convert drop down and convert the .N38 files to .M38. Within this program you will also create a GPS XYZ file, but only after the raw data has been converted.



To convert N38 files select Convert in the program menu and then select the Convert Raw (N38) Files to Profile (M38) Files item. The Convert EM38-MK2 Allegro Files to M38 Format window will appear (Figure 2).

Figure 2. Convert .N38 files to .M38 files

Once the conversion has been completed you can then open and view your survey data in .M38 format (Figure 3). The 2D layout dropdown will give you options to create a Grid or GPS based XYZ, click create GPS XYZ and figure 4 will appear.

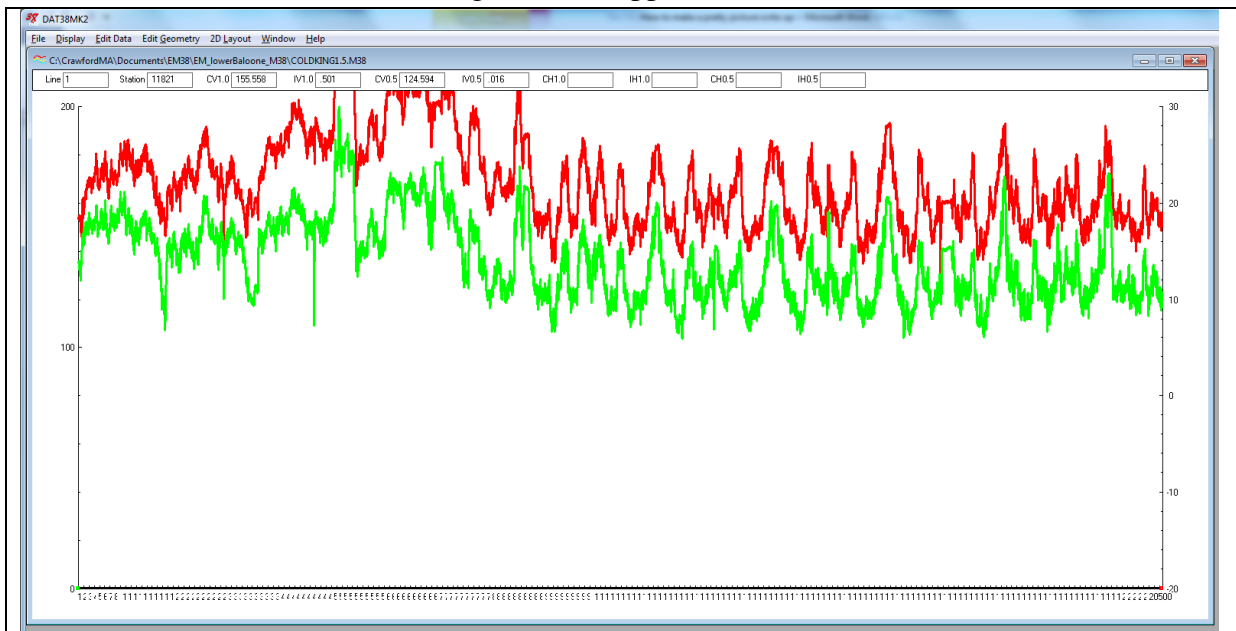
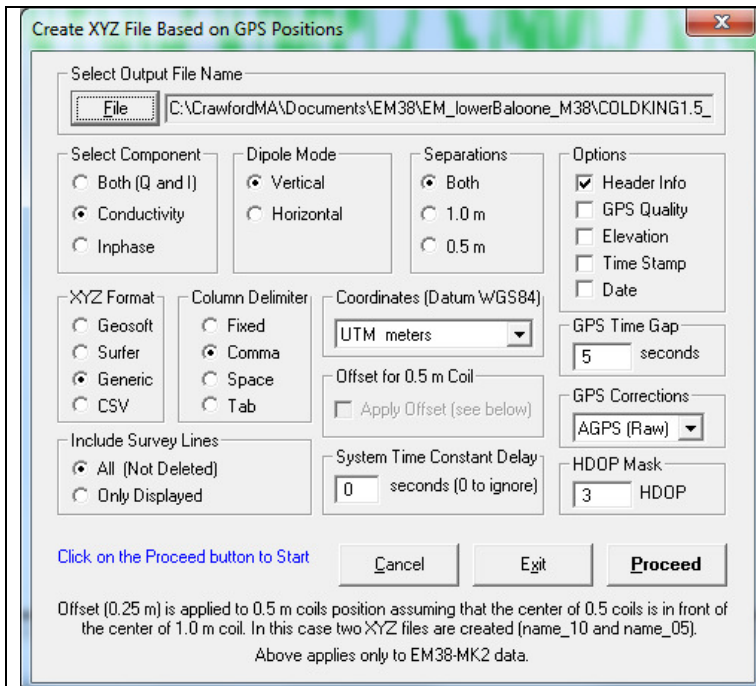


Figure 3. An example of data in the .M38 format

Create GPS Based XYZ File



If EM38-MK2 data is collected together with GPS positioning data then creating a GPS XYZ file is possible, if GPS coordinates are not available then a Grid XYZ option should be used. Before creating the XYZ file the following parameters must to be specified: Select the Output File name, and then Component, Dipole Mode, Separation and Options. Generic XYZ format will create a multicolumn file without any text strings. This file can be used as an input file for many contouring packages.

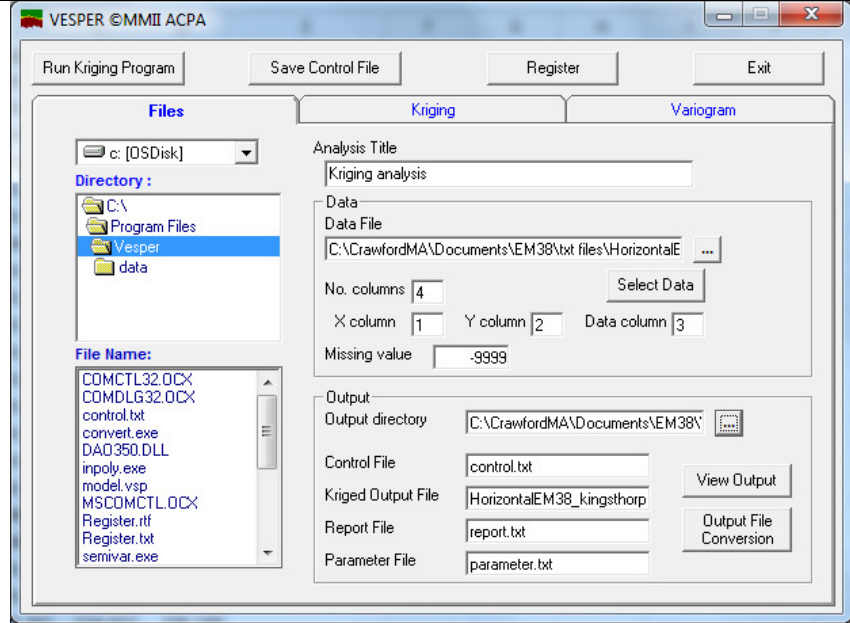
Figure 4 Create GPS Based XYZ File pop up.

Click on proceed to start. Once this process has been completed you can check your data in Excel to make sure it is in the right format and has converted without any data gaps. A simple XY scatter chart

will give you a basic view of your data. For further help with DAT38MK2 please contact <http://www.geonics.com/> or refer to the manual provided on download of program.

VESPER

VESPER (Variogram Estimation and Spatial Prediction with EError) was developed by the Australian Centre for Precision Agriculture (ACPA) for spatial prediction using kriging with local or global variograms. The program can be downloaded and set up quickly and easily, registration cost is only \$50. An unregistered version is available but if the use is commercial then it must be registered and referenced in research articles. Firstly, once the data has been extracted from DAT38MK2 and converted into XYZ format it is prudent to check if the data is in the right format. Open in Excel and order appropriately the X, Y, data columns. Save as txt. (Tab delimited) file. Open Vesper



If you haven't registered a 10 second reminder pops up, but then Figure 5 will be displayed, it contains 3 main tabs. First tab is the data input/ output window, here you import your txt file by clicking select data Figure 6 will pop up. Once you are happy with your selected data fill out the output directory. Note: finish your kriged output file name with .txt

Figure 5. Files window tab of Vesper

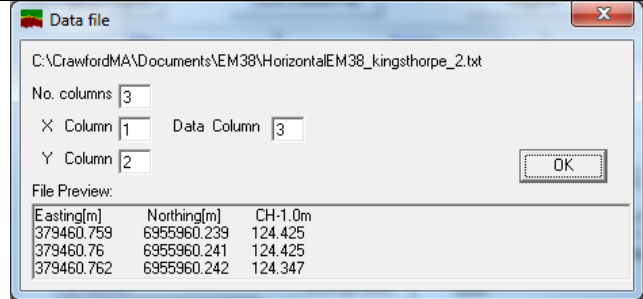
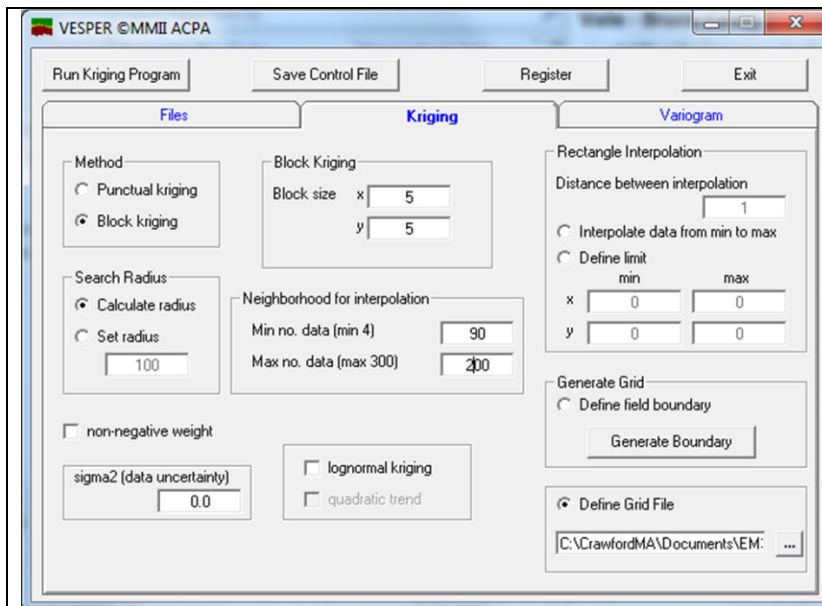


Figure 6. Data file pop up will allow you to check if your data is in the right format. A symbol appears before the data usually indicates a potential problem. In this example it would come before the first number.

Easting[m]	Northing[m]	CH-1.0m
379460.759	6955960.239	124.425
379460.76	6955960.241	124.425
379460.762	6955960.242	124.347



With the kriging tab activated you will be able to generate your grid boundary and grid file, select which kriging method to use for the interpolation and select the neighbourhood for interpolation (Figure 7). First thing to do in this window is to generate your field boundary and define your grid file. These buttons are in the bottom right of Figure 8.

Figure 7. Kriging window tab of Vesper

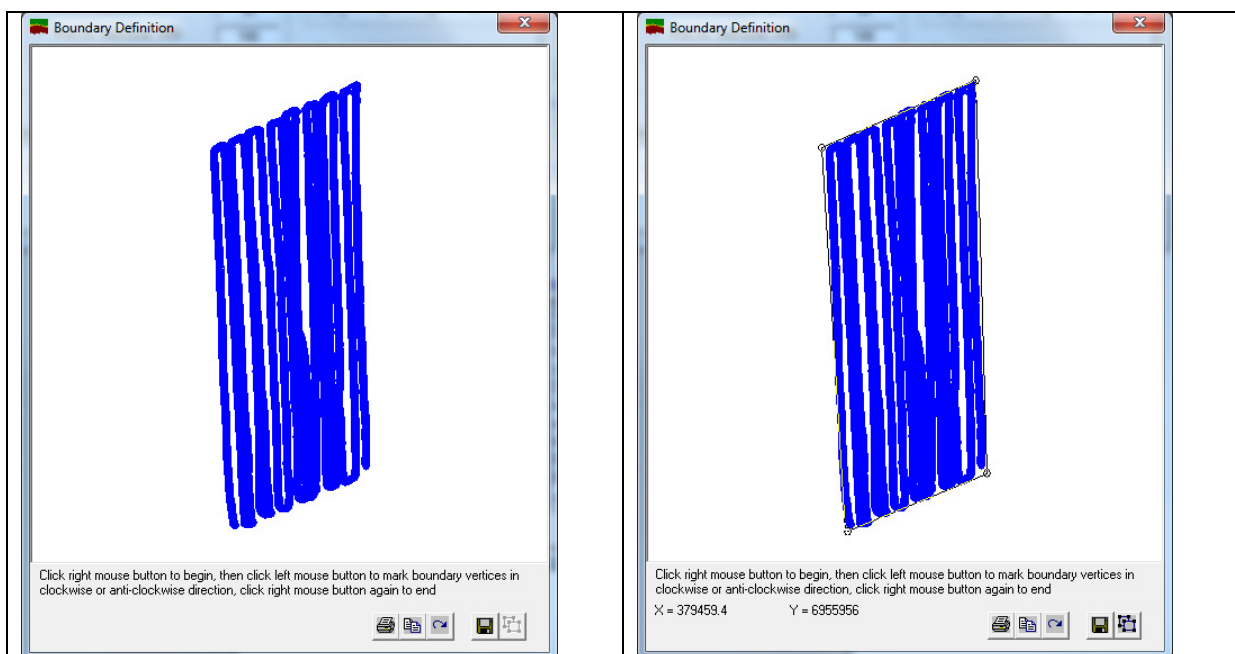
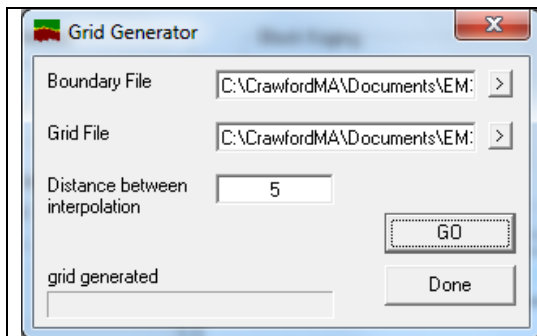


Figure 8. Generating a boundary is simply right click, left click to create the boundary and right click to complete. Note how the button beside the saved button is greyed out in (a)

Once the boundary is saved (example file name House_bnd.txt) a grid can be generated. This can be done by clicking the generate grid button that is now not greyed out. A pop up box appears that will allow the distance in metres to be inputted (Figure 9).



This grid is what you will be interpolating your data onto, for multiple data sources maintaining the same grid size is essential. If comparison over time of ECa is what the aim is then always use the grid generated in the first instance for each interpolation.

Figure 9. Grid Generator pop up box

The difference between the 2 kriging methods is that punctual kriging predicts an exact value at each grid point and assigns that value to the grid point. While block kriging predicts a value that represents a statistically weighted average for an area centred on the grid point. How do different block sizes impact my map? Essentially the larger the area (block size) the smoother the data will appear. An example of different block sizes are shown in Figure 10a,b,c.

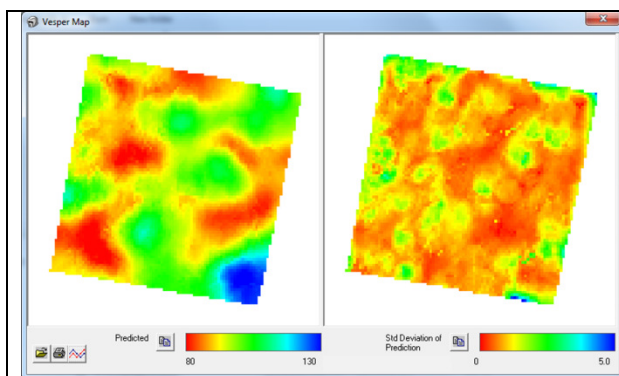


Figure 10a. 1 m interval survey lines, 10m block kriging on 1m grid.

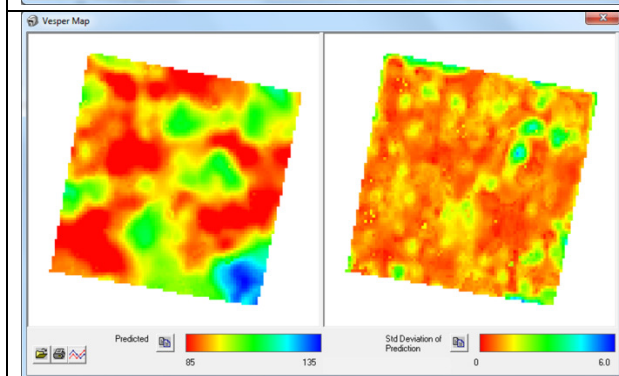


Figure 10b. 1 m interval survey lines, 5m block kriging on 1m grid.

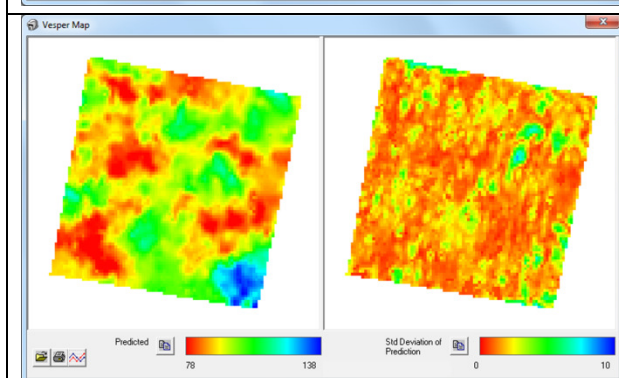
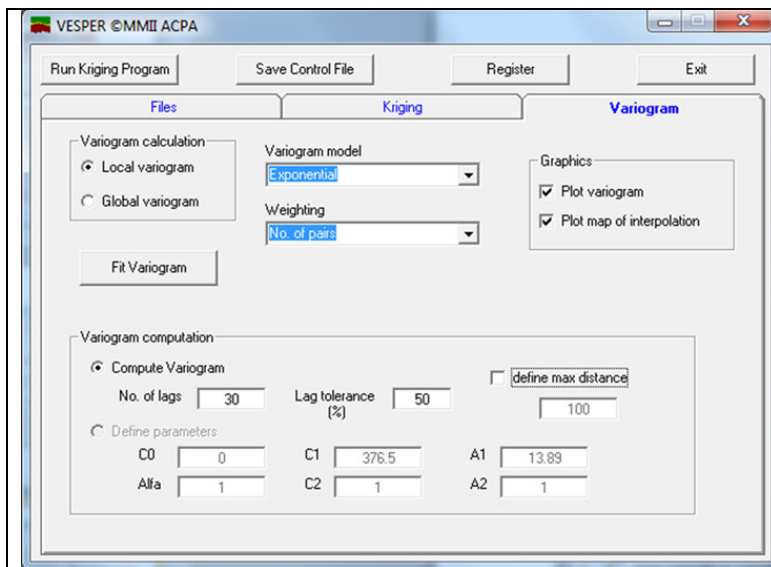


Figure 10c. 1 m interval survey lines, 2m block kriging on 1m grid.



The variogram tab allows you to determine the variogram calculation (Local or Global), model used (Exponential, Gaussian, etc) and the weighting (Figure 11). You can click the Fit Variogram to check if the model selected fits your data, but the default setting of exponential will suffice for this example. Click compute variogram and local variogram calculation.

Figure 11. Variogram window tab in Vesper

Once you are satisfied that everything is in order click Run Kriging Program. If any issues with data entry or setup occurred during the 3 tabs then an error will be displayed and the run will stop. But if you have got it right Figure 12 is what you will see.

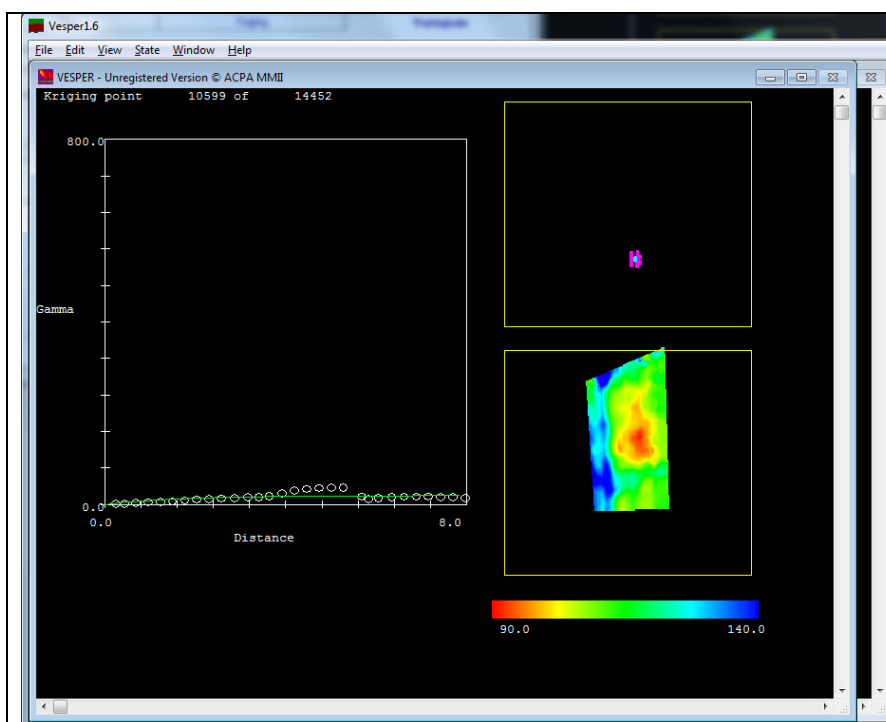
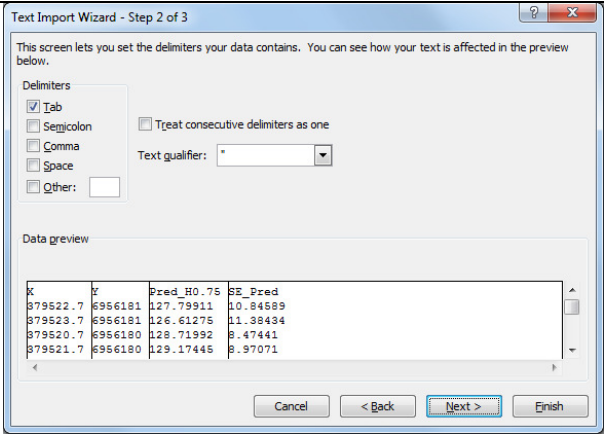


Figure 12. Vesper run program display

For further help with Vesper please contact: Australian Centre for Precision Agriculture, McMillan Bldg, A05 The University of Sydney NSW, Australia, 2006. www.usyd.edu.au/su/agric/acpa E-mail: bmin0925@usyd.edu.au

ArcGIS 10.2.1

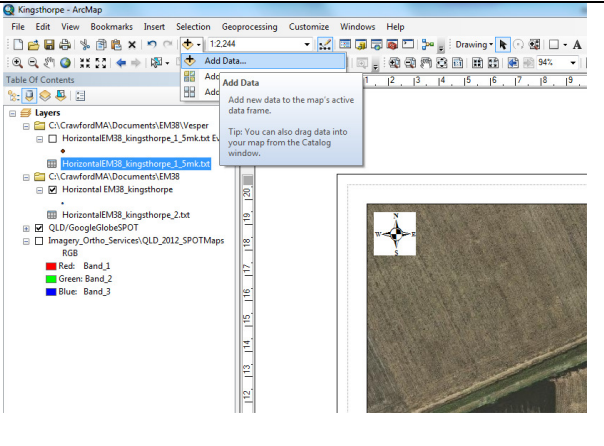
Once the data has been kriged then the process of getting it into ArcGIS is relatively simple, firstly open the kriged file in Excel to check that it is in the right format.



When opening in Excel it will give you the option of how to import the data (Figure 13), once it is in the correct columns save as a txt file.

Figure 13. Text import into Excel of Kriged data

Now open ArcGIS and set up your coordinates for your project area, click on add data (Figure 14) and add your original survey line and the kriged file. To display your data points, right click on the file and click display XY (Figure 15.)



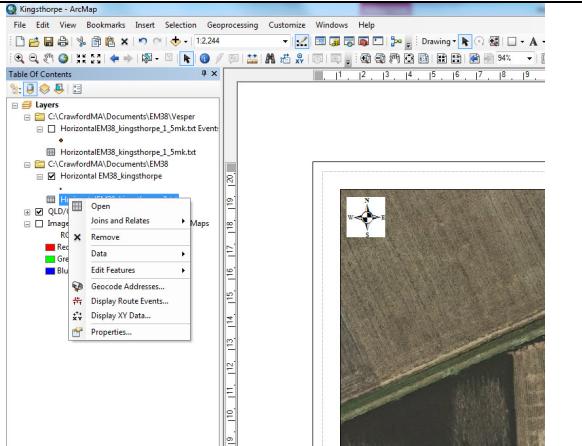


Figure 14. Add data drop down

Figure 15. Display xy data drop down

Your survey line should look like the path you took ☺ (Figure 16) To convert your kriged txt file to a raster click on conversion tools, drop down to feature to raster (Figure 17).



Figure 16. Display of survey line

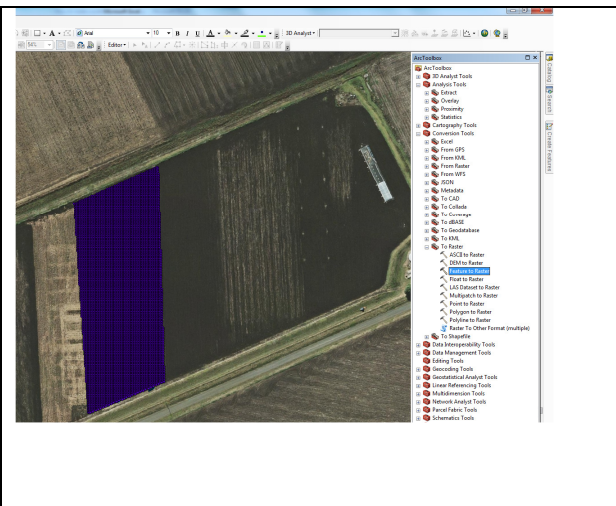


Figure 17. Conversion tools, drop down to feature to raster

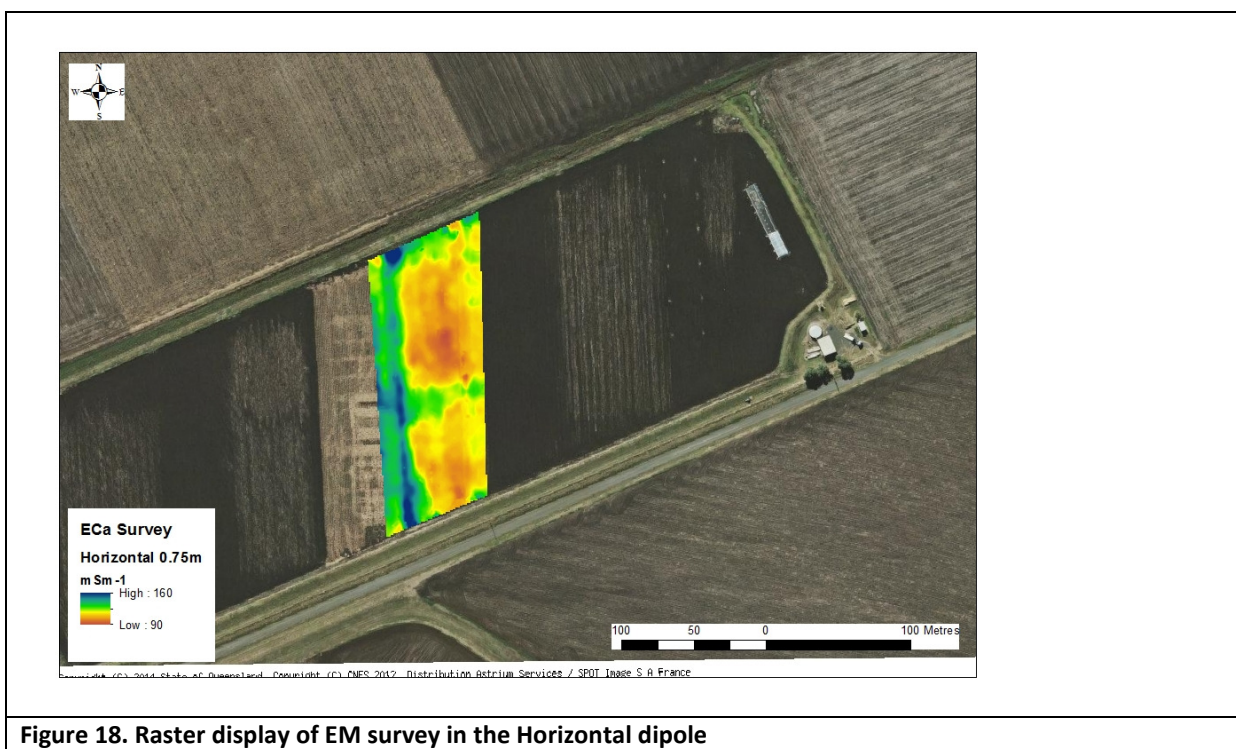


Figure 18. Raster display of EM survey in the Horizontal dipole

For further help with ArcGIS please contact <http://doc.arcgis.com/en/arcgis-online/>

References:

Minasny, B., McBratney, A.B., and Whelan, B.M., 2005. VESPER version 1.62. Australian Centre for Precision Agriculture, McMillan Building A05, The University of Sydney, NSW 2006. <http://www.usyd.edu.au/su/agric/acpa>

DAT38MK2 Version 1.05, COMPUTER PROGRAM MANUAL 2008. Geonics Limited geonics@geonics.com

Depth response function of the EM38

By Jenny Foley, Department of Natural Resources and Mines, Toowoomba.

Different orientations, coil offsets and depths measured (ground level or above) are used to obtain a range of sensing depths. The ECa reading is a weighted average across a depth range, weighted according to the respective depth functions of the different coil orientations and spacings (McNeill, 1980). In the vertical dipole (EM38 placed upright on ground surface) the reading is weighted strongly towards soil attributes at around 0.3-0.6 m depth, declining exponentially to approximately 1.5 m depth (1 m coil spacing). Table 1 shows the proportion of response in each 10 cm depth increment ($R_v(z)$). Note that a small response continues down the profile to around 5 m depth. At 1.5 m only 68% of the signal is accounted for.

Table 1 Vertical one dimensional depth response function for the EM38 - 1 m coil spacing

Depth Z (m)	$R_v(z)$ (vertical dipole) Percent (%)	Proportion	Cumulative response	$R_h(z)$ (horizontal dipole)	Proportion	Cumulative response
0.0	100			100		
0.1	98	2	2	82	18	18
0.2	93	5	7	68	14	32
0.3	86	7	14	57	11	43
0.4	78	8	22	48	9	52
0.5	71	7	29	41	7	59
0.6	64	7	36	36	5	64
0.7	58	6	42	32	4	68
0.8	53	5	47	29	3	71
0.9	49	4	51	26	3	74
1.0	45	4	55	24	2	76
1.1	41	3	59	22	2	78
1.2	38	3	62	20	2	80
1.3	36	3	64	19	1	81
1.4	34	2	66	17	1	83
1.5	32	2	68	16	1	84
1.7	28	3	72	14	2	86
1.9	25	3	75	13	1	87
2.1	23	2	77	12	1	88
2.3	21	2	79	11	1	89
2.8	18	4	82	9	2	91
3.8	13	5	87	7	2	93
5.0	10	3	90	5	2	95

When the device is placed in the horizontal dipole mode (EM38 sideways on ground surface) the reading is weighted strongly towards soil attributes at the surface 0-0.3 m, declining exponentially to approximately 0.75 m. Table 1 shows the proportion of response in each 10 cm depth increment in

the horizontal dipole ($R_h(z)$). Note that a small response continues down the profile to around 3 m depth. At 0.75 m only 70% of the signal is accounted for.

The depth response is simply related to the intercoil spacing, $Z = \text{Depth/Intercoil spacing}$. For other EMI devices and coil spacings i.e. 2 and 3 meter coil spacings, these proportional responses can simply be scaled up.

The EM38-MK2 also has 0.5 m coil spacing and the depth response functions scaled to a 0.5 m intercoil spacing is provided in Table 2.

Table 2 Vertical one dimensional depth response function for the EM38 – 0.5 m coil spacing

Depth Z (m)	$R_v(z)$ (vertical dipole) Percent (%)	Proportion	Cumulative response	$R_h(z)$ (horizontal dipole)	Proportion	Cumulative response
0.1	92.8	7	7	82	32	32
0.2	78.1	15	22	68	20	52
0.3	64.0	14	36	57	12	64
0.4	53.0	11	47	48	8	71
0.5	44.7	8	55	41	5	76
0.6	38.5	6	62	36	4	80
0.7	33.6	5	66	32	3	83
0.8	28.2	5	72	29	3	86
0.9	23.2	5	77	26	3	88
1.0	19.2	4	81	24	3	91

Reference

McNeill, JD 1980, *Electromagnetic terrain conductivity measurement at low induction numbers*, Geonics Limited Ontario, Canada.

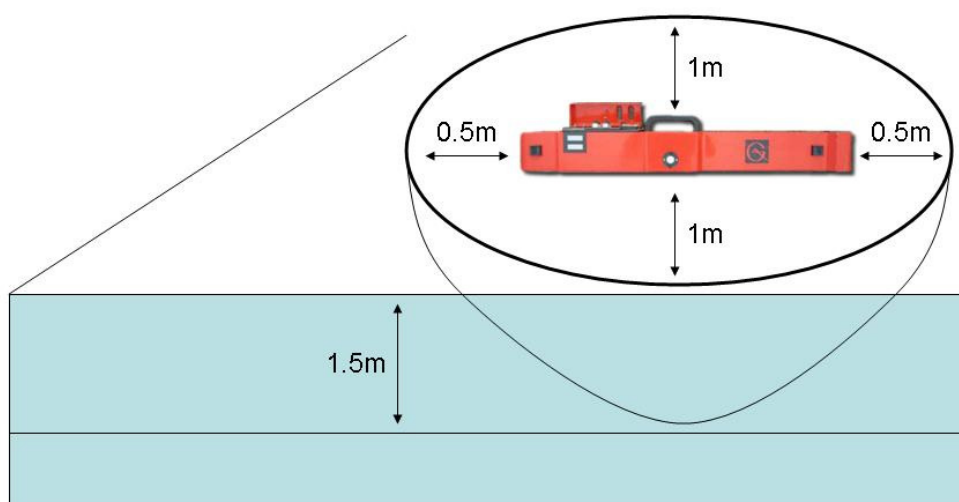
EM38-MK2 Approximate range of sensitivity and response function

In low induction number EMI instruments, signal transmission via a transmitter coil and propagation through soil to a receiver coil occurs in three dimensions (Callegary et al. 2012). The depth response function of McNeill (1980) assumes a one-dimensional understanding of the sensitivity distribution and exploration depth.

Measurement sensitivity distributions depend on the physics of the signal generation and detection, the geometry of the sensor(s) and on the spatial distribution of soil properties. If sensitivity is truly three-dimensional and spatially nonlinear, and involves a sample volume not merely an exploration depth, changes in ECa caused by heterogeneity within the sample volume may be interpreted instead as representing the actual ECa at a particular depth (Callegary et al. 2012).

A comprehensive conceptual understanding of the three-dimensional sample volume and the distribution of spatial sensitivity within that volume is provided for an EM31 in Callegary et al. 2012.

A simple approximate range of sensitivity for the EM38 is shown in the image below. However, in reality this spatial ‘footprint’ is quite complex.



(Image provided by Mike Catalano, GEONICS LIMITED, CANADA)

References

Callegary JB, Ferre TPA, Groom RW (2012) Three-Dimensional Sensitivity Distribution and Sample Volume of Low-Induction-Number Electromagnetic-Induction Instruments. SSSAJ, Vol 76 (1): 85-91.

McNeill, JD 1980, *Electromagnetic terrain conductivity measurement at low induction numbers*, Geonics Limited, Ontario, Canada.

Temperature correction factors calculated for a range of locations in eastern Australia

Dipole	Day of Year	Charleville	Biloela	Narayan	Dalby	Warwick	Moree	Gunnedah	Condobolin	Griffith
Vertical	1	0.86	0.92	0.91	0.99	0.98	0.93	0.98	0.95	0.95
	30	0.85	0.91	0.90	0.97	0.97	0.91	0.96	0.93	0.93
	60	0.86	0.92	0.92	0.99	0.99	0.93	0.98	0.94	0.95
	90	0.91	0.95	0.97	1.02	1.03	0.98	1.03	0.99	1.01
	120	0.97	1.00	1.04	1.08	1.10	1.06	1.10	1.08	1.09
	150	1.05	1.06	1.11	1.14	1.18	1.15	1.19	1.18	1.20
	180	1.12	1.12	1.17	1.19	1.24	1.23	1.26	1.27	1.28
	210	1.15	1.15	1.18	1.21	1.26	1.27	1.28	1.31	1.32
	240	1.12	1.14	1.15	1.19	1.24	1.24	1.26	1.29	1.29
	270	1.06	1.09	1.09	1.14	1.18	1.16	1.19	1.20	1.20
	300	0.98	1.03	1.01	1.08	1.10	1.07	1.11	1.10	1.10
	330	0.92	0.97	0.95	1.03	1.04	0.99	1.03	1.02	1.02
	360	0.87	0.93	0.91	0.99	0.99	0.94	0.98	0.96	0.96
Horizontal	1	0.84	0.90	0.90	0.97	0.96	0.90	0.96	0.91	0.92
	30	0.83	0.89	0.89	0.96	0.96	0.90	0.95	0.90	0.92
	60	0.86	0.91	0.92	0.98	0.98	0.92	0.98	0.93	0.95
	90	0.91	0.96	0.98	1.03	1.04	0.99	1.04	1.00	1.02
	120	1.00	1.03	1.05	1.09	1.12	1.09	1.13	1.11	1.12
	150	1.09	1.10	1.13	1.16	1.21	1.20	1.22	1.24	1.24
	180	1.16	1.16	1.19	1.22	1.27	1.28	1.29	1.34	1.34
	210	1.18	1.18	1.20	1.23	1.29	1.31	1.31	1.37	1.36
	240	1.13	1.15	1.16	1.20	1.25	1.25	1.27	1.31	1.30
	270	1.05	1.08	1.08	1.14	1.17	1.15	1.18	1.19	1.19
	300	0.96	1.01	1.00	1.07	1.08	1.05	1.08	1.07	1.08
	330	0.89	0.95	0.94	1.01	1.01	0.96	1.01	0.98	0.99
	360	0.85	0.90	0.90	0.97	0.97	0.91	0.96	0.92	0.93

Taken from - Huth NI, Poulton PL (2007) An electromagnetic induction method for monitoring variation in soil moisture in agroforestry systems. Australian Journal of Soil Research 45, 63-72.

Soil sampling for volumetric water content

By Jenny Foley, Department of Natural Resources and Mines, Toowoomba.

E_{Ca} (mS/m) readings from your EM38 or other EMI device can be calibrated against cumulative soil water to get a paddock or farm soil calibration. The relationship between E_{Ca} and cumulative volumetric soil water is a simple linear function.

The best way of getting a good calibration is to sample a range of soil moisture conditions. This provides data for a broad range of E_{Ca} readings and improves the linear slope estimate on the calibration curve, which in turn leads to greater accuracy and confidence in estimates of soil water at the wet and dry ends. Several adjacent paddocks can be sampled on uniform soils to get a good range of moistures, including post-harvest (dry), throughout a fallow (filling), after good rains or irrigation (wet), in nearby native vegetation (very dry - provided the salt profile is similar to other places in the paddock - or the soil is very dry).

Soil cores are usually taken with a soil coring rig and bulk density and gravimetric water content sampled in 0.2 m increments. Soil chemistry (particle size analysis and EC) should also be carried out on sub-samples of these cores to check for uniformity in soil texture, salt profiles etc.

In the vertical position, the EM38 effectively measures E_{Ca} to 1.5 m, while in the horizontal position, to 0.75 m. Therefore, to determine calibration equations for these depths in the soil profile, mm of soil water are calculated from volumetric water contents and summed to 0.75 or 1.5 m, then compared by regression with the E_{Ca} measurements.

If using other EMI instruments, soil cores need to be taken to the instrument's respective measurement depths to be able to convert E_{Ca} to total mm of soil water via a soil calibration.

Using a soil coring rig, or hand coring tools, take a sufficient number of cores to sample spatial and soil variability in the paddock/area of interest, for example 1– 3 cores in a small uniform paddock. Coring should occur under suitable conditions, i.e. when the soil is sufficiently dry to access the site with a vehicle, and/or when surface layers are not extensively dry and cracked (particularly when sampling swelling clay soils).

As the cores are taken, they can be cut up for 2 measurements-

- a) Soil bulk density (BD) and gravimetric water contents. The bulk density/water content samples need to be approximately 0.2 m core lengths (length and width of each core accurately recorded) taken either side of the samples to be used for chemistry.
- b) Samples for chemistry analysis to determine soil texture (particle size analysis) and soil salinity (EC).



Photo 1: Soil core cut for BD and chemistry sampling

The 0.2 m core samples are weighed and dried at 105°C for one week, then reweighed to determine gravimetric water content. The core volume measurements are used to calculate BD and volumetric water content. Only the BD is subsequently used. These BD measures are also very useful in estimating drained upper limit (DUL)-

Total Porosity (TP) = $1 - (BD/2.65)$

Soil at saturation (SAT) = TP – entrapped air (~3%)

DUL = SAT – Drainable Porosity (DP)

Drainable Porosity is ~2-5 % for heavy clay soils; up to 20 % for sandy soil

The journey to commercialising this technology in the dairy industry

Presenter - Stewart Spilsbury, FOO Technologies

FOO Technologies

The journey to commercialising large scale soil moisture sampling of pastures in dairying using an EM38

20th July, 2015

Overview



FOO Technologies is a “green evolution” pasture utilisation coaching business for irrigated dairy farmers in East Gippsland, Victoria. I have 10 farms, or just over 1500 hectares that I measure pasture mass weekly using a sonar (APR). That’s around 30,000 paddocks per year. Weekly pasture samples are also analysed for each farm.

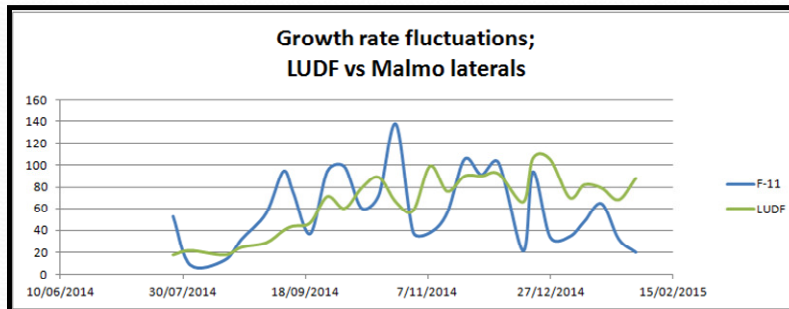
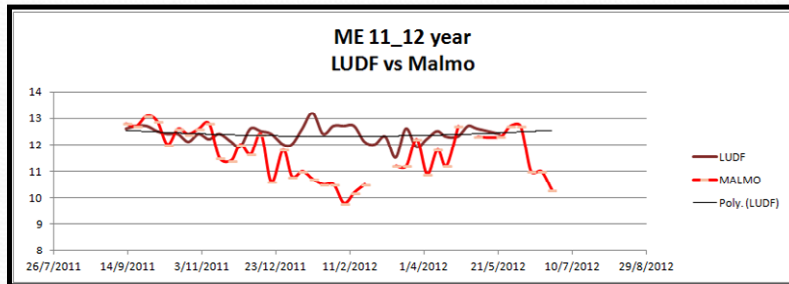
From the data I have collected, it seems to me, our two next largest opportunities for improvement are;

- 2) Water Utilisation Efficiency, and
- 3) Nutrient Utilisation Efficiency (mainly urea), (<http://www.groupone.co.nz/>) via ONE System.

The majority of my farms are flood irrigated, although I have some paddocks under lateral (bike move) sprinklers, some travelling guns, and a couple of pivots.

It is very evident (to me at least), that quality and quantity are significantly superior under the lateral irrigated paddocks. This summer they have grown almost twice the tonnes/Ha of the flood paddocks on the same farm.

The problems...



Why not flood?

Pot trials at Virginia USA (1991) which lasted only 21 days.

Item	Soil moisture		SE ²
	80% FC	Flooded	
Dry matter yield, g pot ⁻¹	111.6**	88.8	4.3
NDF, mg 100mg ⁻¹	34.8**	36.7	0.3
ADF, mg 100mg ⁻¹	21.7*	22.7	0.2
Hemicellulose, mg 100mg ⁻¹	13.1*	14.0	0.2
Cellulose, mg 100mg ⁻¹	16.8	18.0	0.6
Lignin, mg 100mg ⁻¹	2.8	2.9	0.4

- The average cow can only eat approximately 7.5kg of NDF, so if we want an intake of 20kg of DM, at an NDF of 50% or higher, NDF is limiting pasture intakes.
- In addition – farmers are trying to mate cows in November, when feed quality is falling – the flow on effect is very low “in-calf” rates.

The decision process...

Why not use soil moisture probes (Aquaflex etc)

My first thoughts were along these lines – however upon investigation I realised that;

- To use them correctly, a soil survey first needs to be undertaken as we have numerous soil types on farms with years of laser levelling adding to the issue.
- They work well with Pivots or sprinklers where the entire area is watered in one day, but with flood, there are many outlets around the farm and it can take a week or more to water the entire farm.
- Multiple meters would significantly add to the cost per farm
- Intra paddock variation – which is so large an issue with flood – would not show up.

An EM 38 became the final choice.

- Most importantly – with an EM38, I am able to demonstrate to my clients, the impact on growth rates directly related to soil moisture levels **by paddock** and by **irrigation method**.

Proof of concept....

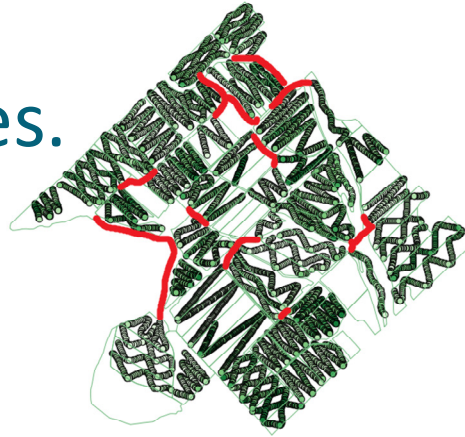
I searched on-line for others using the EM38 for measuring soil moisture.

- EM38 for measuring & mapping soil moisture in cracking clay: PhD student B Hossain (UNE)
- Precision Ag Group, UNE
- Others:
 - Reedy RC and Scanlon BR (2003) Soil water content monitoring using electromagnetic induction. Journal of Geotechnical and Geoenvironmental Engineering 129, 1028-1039
 - Neil Huth¹, Graham Boulton², Neal Dalgliesh², Brett Cocks² and Perry Poulton² Electromagnetic Induction methods for monitoring soil water in irrigated cropping systems
- Jenny Foley.

And I investigated a number of data mapping & analysis platforms;

- ARC GIS
- Farmworks
- Surfer 12

The objectives.



To build a tow mechanism that allowed me to;

- 1) Easily attach and detach the system when not in use, and
- 2) Continue to drive over and under electric fences, and
- 3) Easily retrieve and deploy the EM38 between paddocks – while driving on lanes/roads (**red lines** on map), and
- 4) Continue at roughly the same data collection rate (ha/day) plus be able to quickly automate the data analysis at end of day, and
- 5) Continue to measure the pasture mass off the front of the bike without disruption caused by towing at the back.

Proto-types



The remaining issues.

- 1) Remote throttle for "blipping" bike over fences at distance,
- 2) Software for analysing maximum and minimum numbers for each paddock, so that a total farm, and per paddock soil moisture content can be obtained.

