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

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

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

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

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

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

Methods
Three, one hectare square plots were marked out across a 96 ha field of Vertosol soil planted to cotton at 'Keytah' (ca. 40 km west of Moree, NSW Australia). Each plot represented an EC_a zone identified from a previous, field-wide, EMI survey (low-plot = 80-120; mid-plot =120-145 and high-plot = 160-185 mS/m). Ten polyethylene access tubes (56mm dia. x 1.8m) were inserted into the plant line at randomly selected locations across each plot in October 2011, three weeks after sowing. All tubes were inserted to 1.5 m depth, cut off at 20 cm above the soil surface and capped. The field had 1.5 m wide beds, i.e. plant rows were 1.5

m apart with an irrigation furrow between every second row. Furrow run-lengths were 400 m requiring approximately 4 hours to irrigate. EC_a and neutron probe readings were taken at each access tube over a three month period that included four irrigations and several rainfall events. EC_a readings were taken with the EM38 (Geonics® Ltd. Ontario, Canada) in the vertical mode positioned 0, 20, 40,....140 cm above the soil surface (Hossain *et al.* 2010) in line with the plant row and up against the bed-side of the access tube. Sixteen-second counts were taken at 20, 40…140 cm depths using a neutron moisture probe (Hydroprobe® Boart Longyear, Model 503DR, California USA). Both instruments were used at each access tube on ten to thirteen occasions across: January (16,18,20,22); February(16,19,20,22,24); March (2,12,13,14,15); and April (9,10) in 2012.

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

Results

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

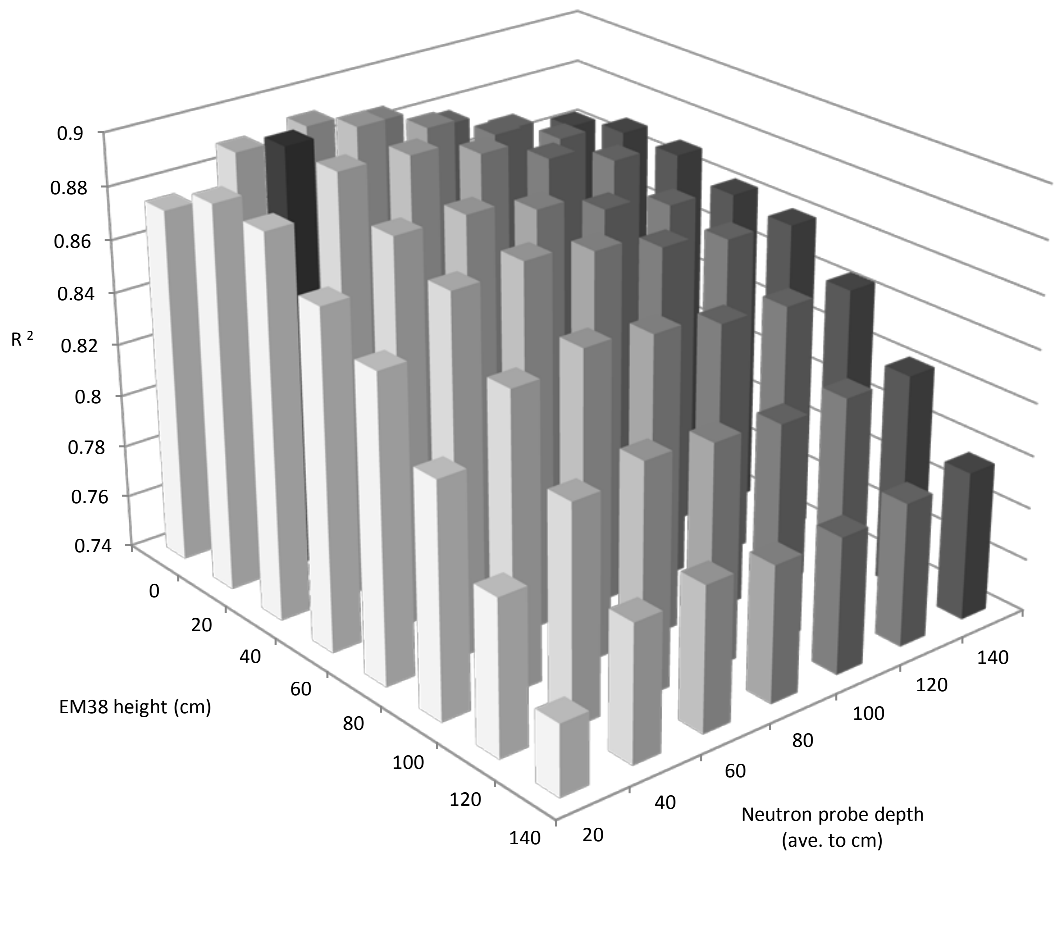

Figure 1. The R^2 for the linear regressions between ECa and corrected neutron probe counts for all combinations of EM38 height above ground and average neutron probe counts to each soil depth. The range of standard errors was 0.009 to 0.024. The dark column at EM38 height 20cm and neutron probe depth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

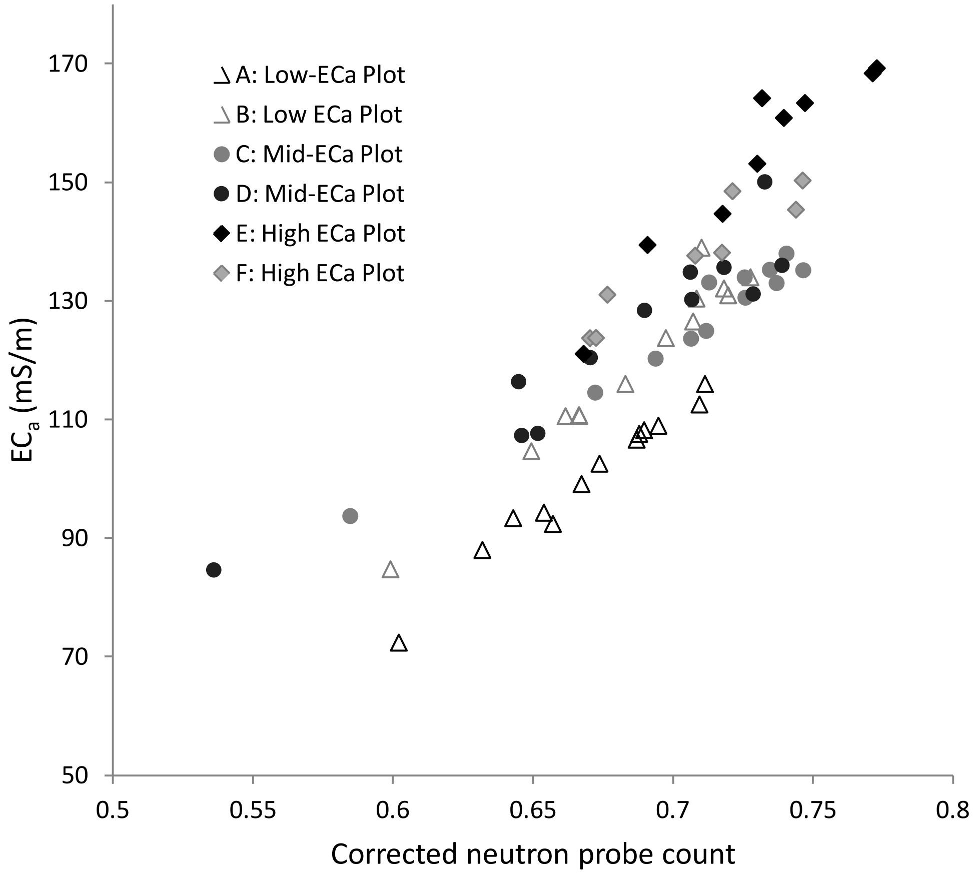

Figure 2. Examples of the linear relationship between EC$_a$ and CNPC for individual tube sites from each EC$_a$ plot for EM38 height 20cm and average neutron probe counts to 40cm. R^2 for: A= 0.98; B= 0.96; C=0.96 D=0.90; E=0.91; F= 0.89.

Discussion

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

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

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

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