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Multiscale soil moisture estimates using static and roving cosmic-ray soil moisture sensors

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Abstract. Soil moisture plays a critical role in land surface processes and as such there has been a recent increase in the number and resolution of satellite soil moisture observations and development of land surface process models with ever increasing resolution. Despite these developments, validation and calibration of these products has been limited because of a lack of observations at corresponding scales. A recently developed mobile soil moisture monitoring platform, known as the 'rover', offers opportunities to overcome this scale issue. This paper describes a research project aimed at producing soil moisture estimates at a range of scales that are commensurate with model and satellite retrievals. Our investigation involved static cosmic ray neutron sensors and rover surveys across both broad (36 x 36 km at 9 km resolution) and intensive (10 x 10 km at 1 km resolution) scales in a cropping district in the Mallee region of Victoria, Australia. We describe approaches for converting rover survey neutron counts to soil moisture and discuss the factors controlling soil moisture variability. Measurements revealed that temporal patterns in soil moisture were preserved through time and regression modelling approaches were utilised to produce time series of property scale soil moisture which may also have application in calibration and validation studies or local farm management. Intensive scale rover surveys produced reliable soil moisture estimates at 1 km resolution while broad scale surveys produced soil moisture estimates at 9 km resolution. We conclude that the multiscale soil moisture products produced in this study are well suited to future analysis of satellite soil moisture retrievals and finer scale soil moisture models.

1 Introduction

Soil moisture has a strong influence of land-atmosphere interactions, hydrological processes, ecosystem functioning and agricultural productivity. The importance of this variable has led to an increase in the number and resolution of satellite soil moisture observations and the ongoing development of finer resolution land surface process models (Ochsner et al., 2013). Despite these developments, our ability to validate and/or calibrate these products is limited because of a lack of observations at matching scales. Satellite observations typically have resolutions in the order of 3 to 50 km, while broad-area modelling of soil moisture variability typically occurs at resolutions >1 km. The scale of these products are orders of magnitude larger than those of traditional in situ sensors which creates an issue because of the well documented small scale variability in soil moisture (Vereecken et al., 2014; Western and Blöschl, 1999). Some researchers have overcome this issue by establishing soil moisture monitoring networks (Bogena et al., 2010; Smith et al., 2012), but the extent of sensor networks is still relatively small (<1 km^2).

More recently cosmic-ray neutron sensors (CRNS) have been deployed to provide soil moisture estimates at a scale hectometres (circular footprint, 260-600 m diameter) (Desilets and Zreda, 2013; Köhli et al., 2015). CRNS sensors measure naturally generated fast neutrons (energy 10–1000 eV) that are produced by cosmic rays passing through the Earth's atmosphere. The neutron intensity above the soil surface is inversely correlated with soil moisture as it responds to the hydrogen contained in the soil and plant water and to a lesser degree to plant and soil carbon compounds (Desilets et al., 2010). The better scale match between the CRNS technique and satellite observations has led to a number of recent studies which compare CRNS observations to satellite observations and modelled soil moisture (e.g. Montzka et al., 2017; Vinodkumar et al., 2017; Holgate et al., 2016; Renzullo et al., 2014; Kędzior and Zawadzki, 2016). Development of networks of CRNS across a number of countries (e.g. USA (Zreda et al., 2012), UK (Evans et al., 2016), Germany (Baatz et al., 2014), and Australia (Hawdon et al., 2014)) is providing useful time series of soil moisture information which will be valuable for years to come.

While the CRNS provides a better match to the scale of satellite retrievals and model estimates there is still a scale mismatch that prevents direct full-scale validation of these products. To address this, a mobile CRNS, called the cosmic-ray rover has been developed (Desilets et al., 2010). The rover uses the same technology as the CRNS but its design allows for mobile mapping of soil moisture across the landscape. This mobile mapping capability allows for soil moisture surveys to be undertaken over areas commensurate with satellite pixels or model domains thereby filling the gap in soil moisture observations (Chrisman and Zreda, 2013). The earliest use of the cosmic-ray rover was for repeated surveys across an area of 25 x 40 km in the Tucson Basin in order to produce a catchment scale water balance (Chrisman and Zreda, 2013). Dong et al. (2014) used a rover to map soil moisture on multiple occasions over a 16 x 10 km and a 34 x 14 km region in Oklahoma with the aim of evaluating satellite soil moisture estimates. More recently Franz et al. (2015) combined rover surveys over a 12 x 12 km area in Nebraska with CRNS measurements to develop a technique for multiscale real-time soil moisture monitoring.

This paper describes part of a research project aimed at producing soil moisture estimates at a range of scales for eventual comparison to satellite and modelled soil moisture estimates. The focus of this paper is on establishing techniques for producing spatial representations of soil moisture using CRNS sensors and a cosmic-ray rover. We will present a nested set of broad scale and intensive scale rover survey results which were collected across a 36 x 36 km area in a cropping district in Mallee region of Victoria, Australia and we will describe techniques used to convert rover measurements into soil moisture estimates using CRNS sensors and spatial soil property information. Using statistical relationships between property scale soil moisture from rover surveys and CRNS sensors we will present a simple approach for producing real-time property-scale soil moisture estimates in the local area. We also use our observations at different scales to test the reliability of our experimental design.

2 Methods

2.1 Site description

The study area is located in the Shire of Buloke in the Mallee region of Victoria, Australia (Figure 1). The measurement campaign took place across a 36 x 36 km region centred on -35.684°S, 142.858°E, which lies between the towns of Birchip to the south and Sea Lake to the north. The Mallee is a rain fed agricultural region with wheat and barley being widely grown. Much of the native vegetation has been removed since European settlement. In the region of interest the landscape is flat with an elevation ranging between 50 to 120 m ASL. The climate of the area is classified as semi-arid with an average annual rainfall of 368 mm, an average minimum temperature in July of 3.6°C and an average maximum temperature in January of 30.7°C (Anwar et al., 2007).

2.2 Static cosmic-ray soil moisture sensors

Cosmic-ray soil moisture sensors were installed at two locations in the designated field survey area (Figure 1). These two locations are named Bishes (northern probe) and Bennetts (southern probe). Each of these sensors included a single polyethylene shielded cosmic-ray probe (CRP-1000B, Hydroinnova, Albuquerque, USA), which monitors neutron intensity in the epithermal to fast neutron energy range. Each system also measured barometric pressure, temperature and relative humidity, which are required for measurement correction procedures. The system was programmed to record data at hourly intervals and was sent via satellite telemetry (Iridium SBD services) in near-real-time to a database on a remote server (cosmoz.csiro.au).

In order to isolate the effect of soil moisture on neutron count measurements it is first necessary to remove variation due to other environmental factors. The largest correction that is required is an adjustment for changes in atmospheric pressure, but there are also corrections required for changes in atmospheric water vapor and changes in the intensity of the incoming neutron flux. The standard correction procedures implemented across the CosmOz network have been described in detail by Hawdon et al. (2014) therefore only a brief summary will be provided here.

Cosmic-ray neutron intensity is particularly sensitive to elevation or the mass of air above the sensor, which is defined as an exponential relationship with barometric pressure (Zreda et al., 2008);

$$f_P = \exp\left[\beta\left(P - P_{ref}\right)\right] \quad \text{Eq. 1}$$

where P is atmospheric pressure (mb) and P_{ref} is the reference atmospheric pressure (mb); which is calculated using standard formulas based on site elevation (NASA, 1976). The atmospheric attenuation coefficient (β , $cm^2\ g^{-1}$ or mb^{-1}) for neutron-generating cosmic rays has been calculated for each of our sites using the method described by Desilets et al. (2006).

Water vapor in the atmosphere has the same neutron moderating capacity as water in the soil and as such will influence the total neutron count (Zreda et al., 2012). A correction factor for atmospheric water vapor effects was developed by Rosolem et al. (2013) and it utilises near surface absolute humidity (ρ_{v0} , $g\ m^{-3}$), which is derived from measurements of temperature, atmospheric pressure and humidity. The correction factor for atmospheric water vapor (f_{wv}) is derived from;

$$f_{wv} = 1 + 0.0054\left(\rho_{v0} - \rho_{v0}^{ref}\right) \quad \text{Eq. 2}$$

where ρ_{v0}^{ref} is the reference absolute humidity, which we set to 0 g m^{-3} (i.e. dry air).

To account for variations in incoming neutron flux an intensity correction factor is calculated by normalising the source intensity to a fixed point in time (Zreda et al., 2012). The correction factor for incoming neutron intensity (f_i) is expressed as;

$$f_i = \frac{I_m}{I_{ref}} \quad \text{Eq. 3}$$

where I_m is the selected neutron monitor counting rate at any particular point in time and I_{ref} is a reference counting rate for the same neutron monitor from an arbitrary fixed point in time which is 1 May 2011. Neutron monitor data is sourced from the Neutron Monitor Database (NMDB; www.nmdb.eu). Both of these sites utilise data from the Lomnický štít Observatory in Slovakia.

The counting rate is also scaled to sea level and high latitude to enable comparison between sensors. Scaling factors for converting counting rate to sea level (f_s) and high latitude (f_l) are described by Desilets and Zreda (2003) and Desilets et al. (2006).

Final corrected counts (N) are calculated using the following equation;

$$N = N_{raw}\left(\frac{f_P f_{wv}}{f_i}\right)\left(\frac{f_s}{f_l}\right) \quad \text{Eq. 4}$$

Where N_{raw} is the uncorrected neutron count from the CRP. Corrected neutron counts were converted to volumetric soil moisture content (θ) using the calibration function generated by Desilets et al. (2010) and modified by Bogena et al. (2013):

$$\theta = \left(\frac{0.0808}{\left(\frac{N}{N_0}\right) - 0.372} - 0.115 - W_{lat} - W_{SOC}\right)\rho_{bd} \quad \text{Eq. 5}$$

where N_0 is the neutron intensity in air above a dry soil which is obtained from field calibration.

Field calibration at each site involved collection of gravimetric and volumetric soil samples at three distances from the probe (25m, 100m and 200m) along each cardinal and inter-cardinal direction (i.e. 8 radial directions). At each sample point, soil cores were taken to calculate volumetric soil moisture content for three depths (0 to 5 cm, 10 to 15 cm, and 25 to 30 cm), giving a total of 72 samples per calibration. Water content from samples was determined by drying samples at 105°C for 24 hours (Klute, 1986). The depth weighted soil moisture from field calibration was calculated using the method proposed by (Franz et al., 2012) and corresponding corrected neutron count is used to determine N_0 in Eq. 5. Hydrogen held within the lattice structure of the soil minerals and organic material can also effect neutron count rate and, hence, need to be considered in calculation procedures. Lattice water (w_{lat}) was determined from the amount of water released at 1000°C preceded by drying at 105°C. Soil organic carbon was estimated by measuring total organic carbon in samples using Heanes wet oxidation, method 6B1 in Rayment and Higginson (1992). Following Franz et al. (2013) and Bogena et al. (2013), the organic carbon was assumed to be present as cellulose, $C_6H_{10}O_5$, and this was converted into an equivalent amount of water (w_{SOM}) by multiplying measured soil organic carbon by 0.556, which is the ratio of five times the molecular weight of water to the molecular weight of cellulose.

2.3 Rover system

The rover system is based around a set of 16 custom made tube capsules supplied by Hydroinnova (Albuquerque, USA), which are similar to those used for the static cosmic-ray soil moisture tubes but larger. The rover has a counting rate ~18 times that of a standard static sensor allowing for measurements to be made at one minute intervals. For a volumetric soil moisture content of 10% a count rate of around 350 c min^{-1} was recorded. The set of 16 tubes is mounted in a trailer from which additional measurements of air temperature, relative humidity, atmospheric pressure and location were also made. While mobile, the measurements from the system were monitored in real-time on a screen in the cabin of the tow vehicle. A dash mounted camera was also used to collect images at one minute intervals during the survey.

For this investigation a nested design of broad scale and intensive localised measurements was implemented. The broad scale design included a survey over an area with dimensions of approximately 36 x 36 km which encapsulated a single Soil Moisture Active Passive (SMAP) satellite pixel. Using typical counting rates for this area and by targeting an output resolution for soil moisture of 9 x 9 km we calculated that the maximum driving speed for this survey was 90 km h^{-1}. This provided a good density of measurement points for interpolation purposes. The survey area and measurement points from the driving track are shown in Figure 2. The broad scale surveys typically took 10 h to complete, involved over 600 measurements and the average speed travelled was around 60 km h^{-1}. The intensive scale survey covered an area of approximately 10 x 10 km and was located in the south eastern corner of the broad scale survey (Figure 2). In this survey a target resolution for soil moisture of 1 x 1 km was used for which we calculated that the maximum driving speed should not exceed 30 km h^{-1}. Much of the driving for the intensive scale surveys was around field boundaries and on unsealed roads. Intensive scale surveys also took approximately 10 h to complete with more than 600 measurement point being collected. The average speed during these surveys was 20 km h^{-1}. Survey tracks were defined for both surveys prior to undertaking measurement using maps of the local road network. These maps were loaded into GIS software and were used to guide navigation on each survey run.

Procedures used for correcting static cosmic-ray neutron sensor counts (Eq. 1 to Eq. 4) were also applied to the rover data. Continually varying elevation, location, pressure, temperature and humidity were used for these calculations. Soil moisture was also calculated in the same way as for the static sensors (Eq. 5) but there was a requirement for spatial information regarding bulk density, soil organic matter and lattice water content. The Soil and Landscape Grid of Australia provides ~90 x ~90 m pixels of digital soil attributes including bulk density (Viscarra Rossel et al., 2014a) and soil organic carbon (Viscarra Rossel et al., 2014c) at depths of 0-5 cm, 5-15 cm and 15-30 cm which are useful for applying to rover surveys. The Soil and Landscape Grid of Australia does not provide any lattice water information but it does provide information on clay content (Viscarra Rossel et al., 2014b) and others (Greacen, 1981; Avery et al., 2016) have shown that clay content is often a good predictor of lattice water. As an additional part of this study we investigated whether such a relationship existing for the soils in the study area. To do this we collected 36 samples for lattice water analysis; this included 25 distributed samples in the broad scale survey area, 9 samples across the intensive scale survey area and the 2 samples collected as part of the calibration of the static probes. These samples were from cores extracted from 0-30 cm depth. The spatial maps of bulk density, clay content and organic carbon used in the rover calculation procedures are shown in Figure 3, also shown for site characterisation is the digital elevation model for the survey area.

Use of Eq. 5 in rover surveys also requires specification of a suitable N_0 value. For the static sensors this value is derived through the calibration procedures. To calculate N_0 for the rover we undertook side-by-side comparisons with the static sensors which involved parking next to a static sensor for 12 hours prior to a survey. The average counts from the rover and static sensor were then compared to derive a suitable scaling approach to derive a rover-specific N_0. Both broad scale and intensive scale surveys were undertaken on three separate occasions on consecutive days during April 2016, June 2016 and March 2017.

Interpolation of the rover count data was required to produce a spatial representation of count rates for the entire survey area. To achieve this the Variogram Estimation and Spatial Prediction with Error (VESPER) software package (Minasny et al., 2005) was used. VESPER was used to undertake conventional kriging with a global variogram. An exponential variogram model was used for both survey scales and an interpolated grid of corrected rover count rate was produced at 90 m resolution to match that of the underlying soils information.

3 Results

3.1 Static CRNS calibration

Prior to deployment, the two static sensors were run side-by-side for a period of 4 days to determine if there were any differences in counting rates that were not attributable to local conditions. Over this period the average counting rate differed by less than 1%, thus giving confidence that differences between sensors reflect local site characteristics alone. Calibration of the two CRNS occurred under different soil moisture conditions; at Bennetts the depth weighted soil moisture content was 0.13 $m^3 m^{-3}$, while at Bishes it was 0.08 $m^3 m^{-3}$. Fitting of the calibration curve to these two sites resulted in remarkable similarity in derived dry soil (N_0) counting rates with analysis of the data collected at Bennetts producing an N_0 of 1541 c h^{-1} and that from Bishes producing an N_0 of 1583 c h^{-1}. These differences are very small and reflect the fact that hydrogen represented by the biomass pool is basically non-existent at these sites.

3.2 Rover calibration

Calibration of the rover was undertaken through side-by-side comparison with the Bennetts CRNS and the Bishes CRNS on two separate occasions each. These comparisons covered a range of soil moisture conditions over four separate 12 h periods. Table 1 shows the corresponding neutron count rate for the rover and each CRNS and the scaling factor that converts static CRNS counting rate to a rover equivalent; this scaling factor is used to scale the N_0 values derived for each static sensor to an equivalent N_0 for the rover. Despite the differences in conditions and site characteristics, the scaling factor remained relatively constant, as did the derived N_0 for each comparison period. Given the relatively constant relationship between the rover and static sensors an average N_0 of 460 c min^{-1} was derived and this value was applied across all surveys.

3.3 Spatial lattice water information

The volumetric soil moisture equation for cosmic-ray soil moisture measurements (Eq. 5) requires information on soil organic matter content, bulk density and lattice water. For our rover surveys spatial data sets exist for organic matter and bulk density but not for lattice water. A relationship between clay content and lattice water content has been noted by others therefore samples were collected to test for similar relationships across our survey area. A comparison of clay content and lattice water content for 36 spatially distributed samples shows a strong linear relationship (R^2 =0.7) across a broad range of clay content (4–56%). This relationship was applied to the spatial clay content data set from the Soil and Landscape Grid of Australia (Viscarra Rossel et al., 2014b) to produce an equivalent lattice water dataset at 90 m resolution.

3.4 Spatial estimation

Example variograms from the kriging procedures used for broad scale and intensive surveys are shown in Figure 6. Both surveys utilise exponential variogram models however the fit is different with the intensive scale surveys having a distinct ‘sill’ and broad scale variograms showing no ‘sill’ at all. The variogram model for the intensive surveys showed more cyclicity (or ‘hole effect’) which could be related to underlying geological periodicity (Yang and Kaleita, 2007). The empirical variograms were well described by the exponential models giving confidence in interpolated rover counts across the respective survey areas.

3.5 Intensive scale rover surveys

Interpolated counts and derived volumetric soil moisture content for each of the three intensive scale surveys is shown in Figure 7. A large range in soil moisture content was observed over the three surveys with values ranging between 0.01 m^3 m^{-3} in April 2016 through to 0.30 m^3 m^{-3} in June 16. Higher than average counting rates and, hence, lower soil moisture were consistently observed in the central northern region of the survey area. This area is characterised by a ridge of sandy soil with rock fragments and is known locally as ‘Sandhill’. Wetter soil moisture conditions were observed through the central and southern parts of the survey area. We note here that although the data are presented at 90 m resolution this is due to calculations being undertaken at the scale of the underlying soil grid; the intended output of this survey is a 1 x 1 km soil moisture product.

Comparison of intensive rover survey soil moisture estimates for the CRNS locations at the three different survey dates shows excellent agreement between the two measurement methods (Figure 8). The rover survey estimate is taken from the 1 km resolution soil moisture estimate for the corresponding CRNS pixel. Comparisons of estimates for the Bennetts CRNS shows differences of less than 0.025 m^3 m^{-3} for all three occasions. The rover survey estimates tended to underestimate the soil moisture measured at the Bishes CRNS. The largest difference was during the April 2016 survey where soil moisture was underestimated by 0.04 m^3 m^{-3}. It is possible that this underestimation is a result of local interpolation issues. The Bishes CRNS is in close proximity to the sandy ridge known as 'Sandhill' which represents a distinct zone of low soil moisture (Figure 7). The effect of this abrupt change is likely to be 'smoothed' within the area that also encompasses the Bishes CRNS.

The rover surveys at the intensive scale also offer the opportunity to estimate soil moisture at the farm property scale. A number of properties in the intensive scale zone are identified in Figure 9 and the intensive scale rover survey from March 2017 has been used to derive property average soil moisture conditions. The average size of the identified properties is approximately 1 km^2. As well as enabling direct estimates at the time of the surveys there is also the opportunity to combine property average soil moisture content at the survey times and CRNS observations in a regression analysis approach to derive a much higher time resolution soil moisture product at the property scale. This approach assumes that rainfall is relatively uniform across the region and that crops are planted across all periods; both of which are typical in this study area. Regression relationships were developed between the Bennetts CRNS and 50 properties in the intensive survey area (see Table A1). Point-to-area regression analysis showed very strong linear relationships with an average R^2 value of 0.97 (range = 0.87-1.00). Application of these regression models to derive time-series of property scale soil moisture for three example properties is given in Figure 10. We note that the opportunity also exists to use similar point-to-area scaling techniques to derive high temporal resolution soil moisture products at other set resolutions (e.g. 1 km) which would make for ideal datasets for testing model and satellite soil moisture estimates.

3.6 Broad scale rover surveys

Interpolated counts and derived volumetric soil moisture content for each of the three broad scale surveys is shown in Figure 11. The common feature of all of the survey dates is the tendency for higher counts and, hence, lower soil moisture to occur at the north-western region of the survey area and lower counts and, hence higher soil moisture to occur in the south-eastern region. These patterns reflect soil textures in the region with sandier soils and dunes with low clay content in the north-western and higher clay content soils in south-east. The driest soil moisture conditions were experienced during the April 2016 survey with a mean soil moisture of 0.05 m^3 m^{-3} (range = 0.01–0.10 m^3 m^{-3}) and the wettest were observed during the June 2016 survey with a mean soil moisture of 0.17 m^3 m^{-3} (range = 0.09–0.27 m^3 m^{-3}). The March 2017 survey provided intermediate soil moisture conditions with a mean for the region of 0.09 m^3 m^{-3} (range = 0.04–0.15 m^3 m^{-3}).

The nested design of the intensive and broad scale surveys (Figure 2) enables the accuracy of broad scale survey estimates to be assessed. To undertake such an analysis, we selected a 9 x 9 km region within the area of survey overlap (Figure 2) and derived corresponding soil moisture estimates at resolutions of 1, 3 and 9 km. The intensive survey results can be considered as a point of truth for broad survey results. The difference in soil moisture estimates between the broad and intensive scale surveys for different resolutions on each of the three survey dates is shown in Figure 12. The broad scale survey estimates are clearly not a good representation of 1 x 1 km scale soil moisture as survey speeds and sampling points are not detailed enough to pick up local soil moisture variations. Differences of up to ±0.10 $m^3 m^{-3}$ were observed. At 3 x 3 km resolution the performance of the broad scale survey estimates improves but there are still some distinct zones where soil moisture differed by as much as ±0.06 $m^3 m^{-3}$. At the 9 x 9 km scale, for which the broad scale surveys were designed, differences in soil moisture between the intensive and broad scale surveys was minimal. On all three occasions the difference was less than 0.005 $m^3 m^{-3}$. These comparisons validate our broad scale experimental design and give confidence in the 9 x 9 km resolution soil moisture produced from our rover surveys.

4 Discussion

Static CRNS calibration at Bishes and Bennetts produced very similar dry soil counting rate (N_0). This similarity has resulted because hydrogen in soil water, lattice water and organic matter is accounted for in the calibration process and because both sites are devoid of above ground biomass. The effect of biomass on N_0 has been noted by Hawdon et al. (2014) who compared N_0 values from eight probes from across the Australian CRNS network with site biomass and also by Baatz et al. (2015) who proposed an empirical biomass correction for CRNS calibration. This finding has important implications for rover surveys in this region as the landscape in the Mallee region is almost entirely cleared of forest and above ground biomass is represented by pasture and crop cover. McJannet et al. (2014) calculated that pasture represented a biomass water equivalent of just 0.6 mm a value similar to that derived by Baatz et al. (2015) for areas dominated by crops; these small values show that these small hydrogen pools will to have little impact on neutron counts (McJannet et al., 2014).

In this present study the N_0 value for converting rover neutron counting rates to soil moisture content was derived through side by side comparison with the two CRNS sensors. A similar approach was employed by Chrisman and Zreda (2013) using a single CRNS as a reference point and by Dong et al. (2014) using a network of in situ measurements. Rover surveys undertaken by Franz et al. (2015) also used comparison with static CRNS sensors but in their investigations a further correction was introduced to account for variations in above ground biomass. Locations will greater biomass should adopt a calibration schemes that include this hydrogen pool (i.e. Baatz et al., 2015; Franz et al., 2013).

Rover surveys require information on the spatial variation in bulk density, soil organic matter and lattice water for calculation of soil moisture content using conventional approaches. While pre-existing bulk density and organic matter datasets exist for Australia we had to derive a lattice water dataset based on a strong region-wide relationship with clay content. The relationship we derived for the study area was different to that proposed by Greacen (1981) for Australian soils and may reflect differences in the soil types included in the analysis. With the intent of producing a similar spatial lattice water dataset for the continental United States, Avery et al.

(2016) derived relationships with clay content but found that relationships were weak for many soil taxonomic group. For best local results a spatial sampling such as that utilised in this present study is recommended.
A factor that has not been accounted for in our rover surveys is the potential impacts of roads on our survey results. By design roads will have a low moisture content and the impact of this narrow strip within the sensor footprint on survey results has not yet been accounted for in rover studies reported in the literature. Using neutron modelling approaches Köhli et al. (2015) demonstrated that a CRNS is most sensitive to soil moisture in the nearest tens of metres and showed that dry roads can contribute to an over estimate of neutron counts by a few percent. In the survey areas in which our broad scale rover surveys were undertaken more than 70% of the roads were unsealed and many of the sealed roads were only one lane wide; while this does not remove the issue it does lessen the potential impact on reported results considerably. The impact of roads on our intensive scale surveys is likely to be even less as 60% of the observations were made while driving around property boundaries (i.e. not properly formed roads) and a further 30% were on unsealed roads. While the impact of roads may not be a major issue for the present study it is an issue that needs some warrants consideration in future surveys.

Intensive scale surveys were designed to produce a 1 x 1 km resolution soil moisture product and comparison to static CRNS observations supports this. Detailed soil moisture maps highlight the impact that soil properties have on observed soil moisture with sandier locations being typically drier when compared to those with more clay. Property scale soil moisture estimates led to the development of point-to-area style regression models which then enabled continuous estimates of soil moisture to be made at the property scale. The regression modelling showed that temporal patterns in soil moisture were strong. Similar observations have been reported for other studies (Kachanoski and Jong, 1988; Grayson and Western, 1998; Vachaud et al., 1985). According to Yang and Kaleita (2007) spatial patterns of soil moisture exhibit some degree of temporal stability which is related to time invariant attributes such as topography and soil characteristics. With the relatively flat topography in Mallee study area and the assumption that rainfall inputs and crop growth are similar between properties, it is likely that differences in the slopes and intercepts of relationship between CRNS observations and property scale soil moisture (see Table A1) are being controlled by local soil characteristics. Changes in local crops and local scale differences in rainfall inputs (i.e. small convective storms) do of course have the potential to change these point-to-area relationships but if these factors can be accounted for then useful spatial and temporal soil moisture datasets can be produced.

Broad scale surveys produced reliable soil moisture estimates at 9 x 9 km resolution although the faster survey speeds and lower measurement density meant that this survey was unable to distinguish many of the smaller scale soil moisture variations revealed at the finer resolution and slower survey speeds of the intensive scale survey. This clearly supports the need to design rover surveys for the scale of analysis to be eventually undertaken.

5 Conclusion

In this study we presented an investigation designed to produce soil moisture estimates across a range of scales. Our investigation involved static CRNS sensors and rover surveys at both broad and intensive scales. We established techniques for converting neutron counting rates from the rover to soil moisture using side-by-side comparisons with static CRNS sensors and spatial datasets of soil characteristics. In particular we found that lattice water was strongly related to clay content in the study area and used this relationship to derive a spatial representation of lattice water.

Rover surveys were undertaken across soils ranging in moisture content from 0.01 to 0.30 m^3 m^{-3} and reliable results were produced across all conditions. The slower driving speeds and denser sampling network of the intensive surveys provided representation of local soil moisture variations at resolutions down to 1 x 1 km. Stability in observed spatial patterns of soil moisture were used in a regression modelling approach to produce time series of property scale soil moisture based on CRNS observations. Broad scale surveys, which incorporated higher driving speeds and sparser sampling points, were shown to produce excellent representations of soil moisture at 9 x 9 km pixel resolution making them well suited for assessing variation in this parameter at a regional scale. The multiscale application of the rover makes it a unique tool for addressing soil moisture questions across scales previously not possible. The multiscale soil moisture products produced in this study are well suited to future analysis of both satellite soil moisture retrievals and finer scale soil moisture models.

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6 Tables and captions

Table 1. Side-by-side comparison of average neutron counts for the static CRNS's (Bishes and Bennetts) and the rover for 4 different 12 hour periods. Also shown are the static CRP to rover scaling factors and derived dry soil counting rate, N_0, for the rover. All counts are in c min^{-1} for application to rover data.

Date	Site	Static CRNS average counts (c min^{-1})	Rover average counts (c min^{-1})	Static to rover scaling factor	Static CRNS N_0 (c min^{-1})	Derived rover N_0 (c min^{-1})
10 April 2016	Bishes	21.74	370.0	17.0	26.4	449
1 March 2017	Bishes	20.4	364.8	17.9	26.4	471
9 June 2016	Bennetts	15.23	268.1	17.6	25.7	452
2 March 2017	Bennetts	16.8	307.6	16.8	25.7	469
			Average	**17.3**	**Average**	**460**

7 Figures and captions

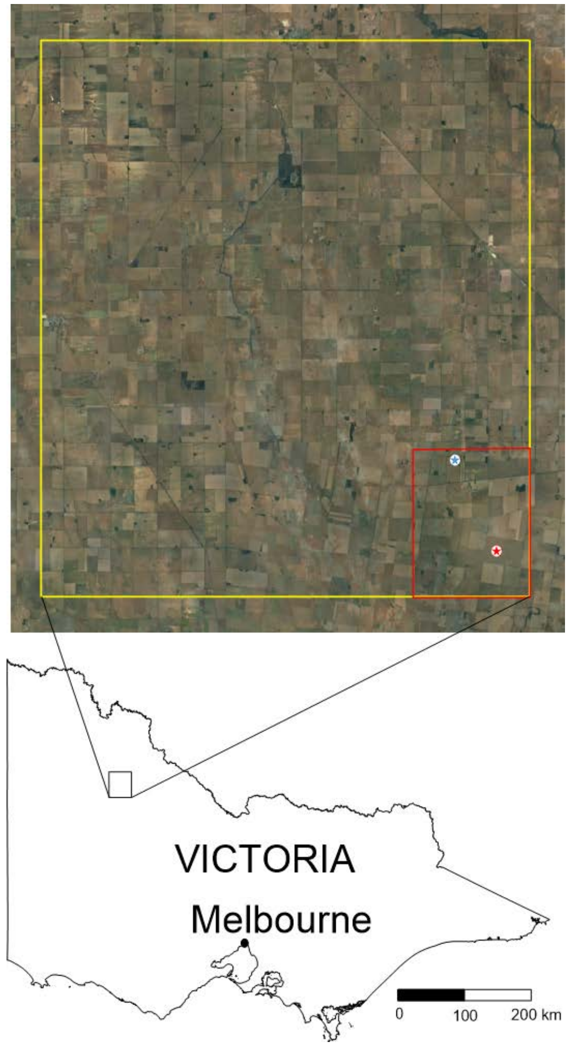

Figure 1. Location of field site in western Victoria, Australia. Yellow rectangle shows extent of broad scale rover surveys and red rectangle shows extent of intensive surveys. Blue and red stars indicate the location of the Bishes and Bennetts cosmic-ray soil moisture sensors. Imagery data: Google, TerraMetrics 2017.

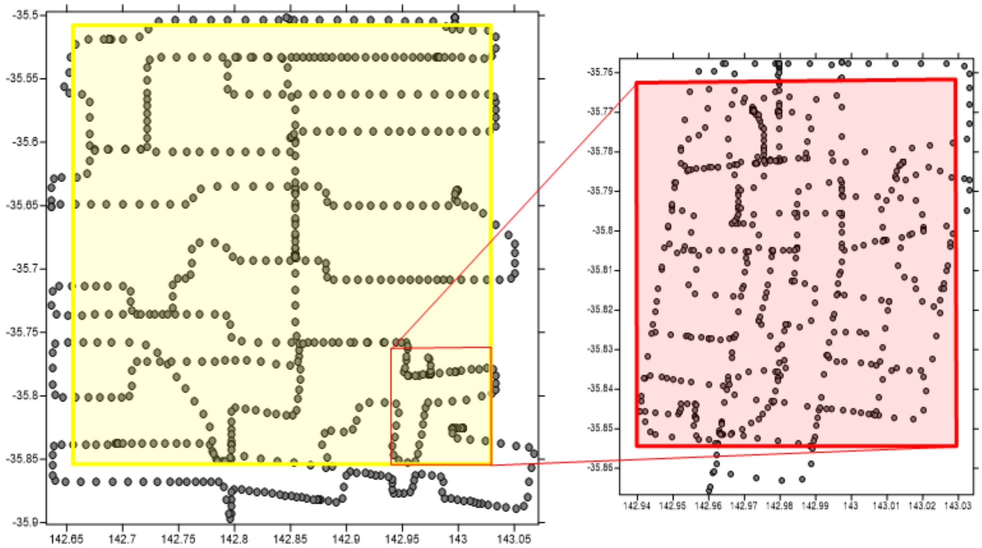

Figure 2. Rover survey extents and sampling points for the broad scale and intensive scale measurement campaigns. Sampling points from April 2016. The yellow box (~36km x 36km) delineates the broad scale survey extent and the red box (~10km x 10 km) delineates the intensive scale survey extent.

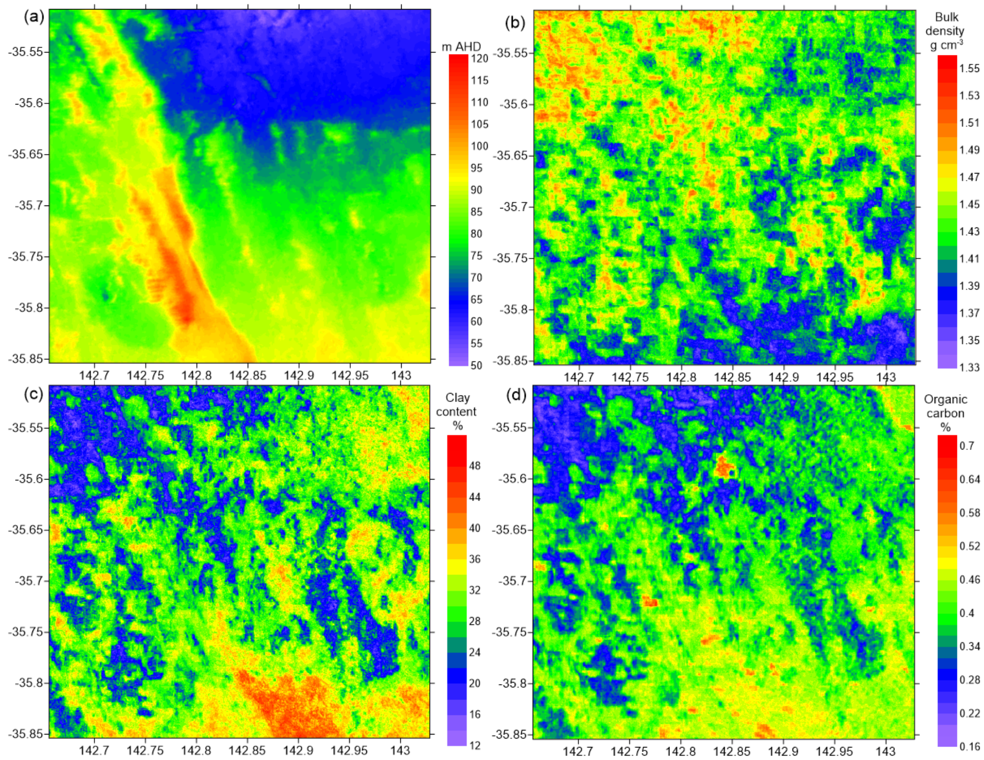

Figure 3. Field survey area DEM (a), depth weighted 0–30 cm bulk density (b), depth weighted 0–30 cm clay content (c), and depth weighted 0–30 cm organic matter content (d).

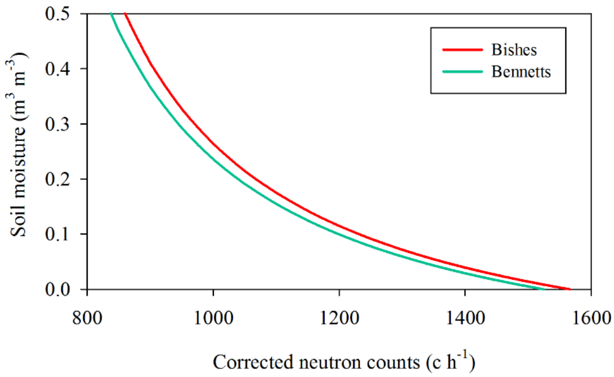

Figure 4. Calibration curves for converting corrected neutron counts to soil moisture content for the Bishes and Bennetts cosmic ray soil moisture sensors. The dry soil counting rate, N_0, is 1583 c h^{-1} for Bishes and 1541 c h^{-1} for Bennetts.

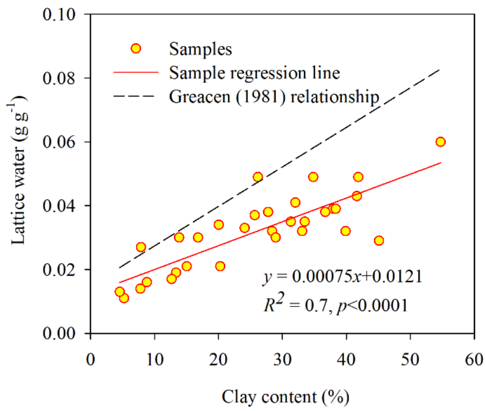

Figure 5. Clay content vs Lattice water showing sample points from the study area and fitted relationship. Also shown for reference is the relationship proposed by Greacen (1981).

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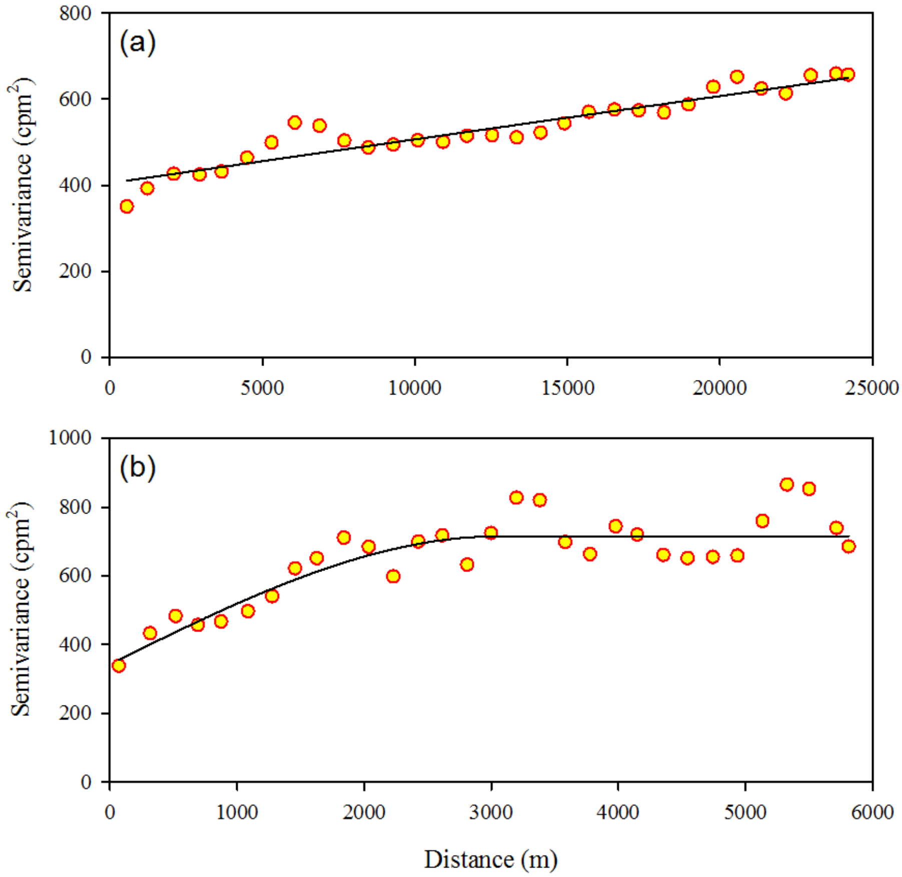

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550 **Figure 6. Example variograms used for block kriging for broad scale and intensive surveys. The broad scale**
551 **variogram is from April 2016 (a) and the intensive scale variogram is from June 2016 (b).**
552
553

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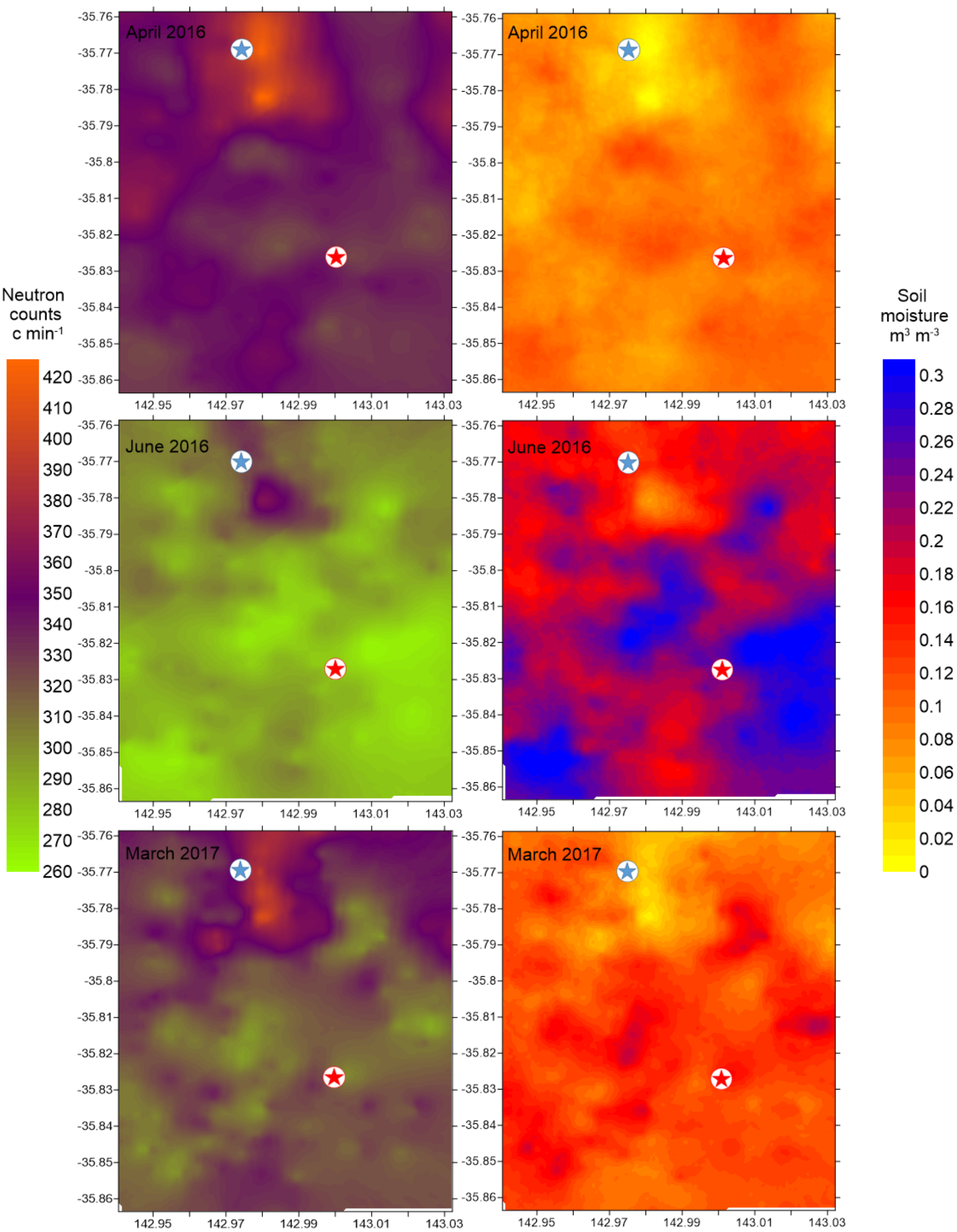

Figure 7. Interpolated counts (left column) and derived soil moisture (right column) for the three intensive scale surveys during April 2016, June 2016 and March 2017. Blue and red stars indicate the location of the Bishes and Bennetts cosmic-ray soil moisture sensors.

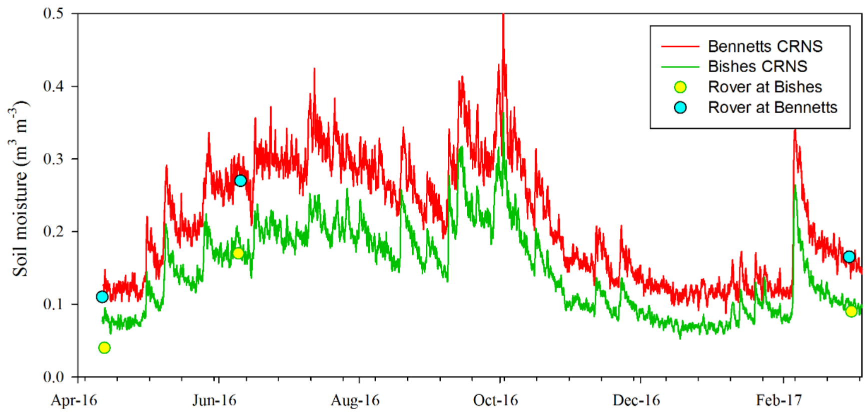

Figure 8. Comparison of Bennetts and Bishes CRNS soil moisture estimates and corresponding intensive rover survey estimates for the CRNS locations for the three survey dates. Rover survey estimate is from 1 km resolution pixel corresponding to each CRNS location.

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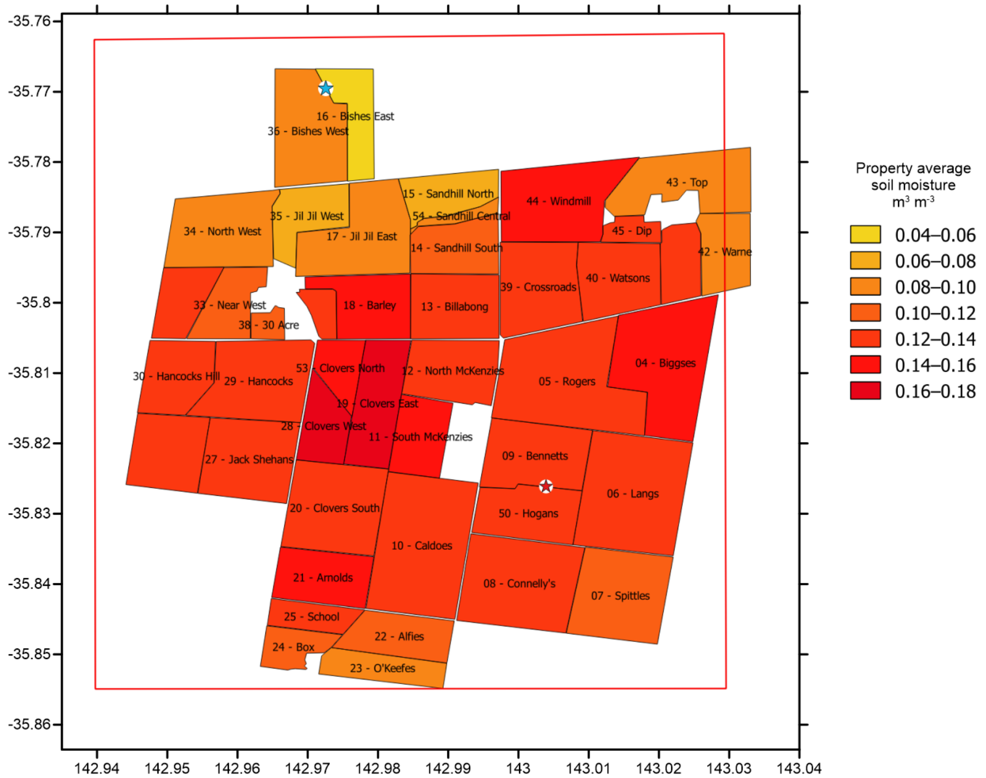

Figure 9. Location of target properties within the intensive scale survey area (red box) and property average soil moisture content for March 2017. Blue and red stars indicate the location of the Bishes and Bennetts cosmic-ray soil moisture sensors.

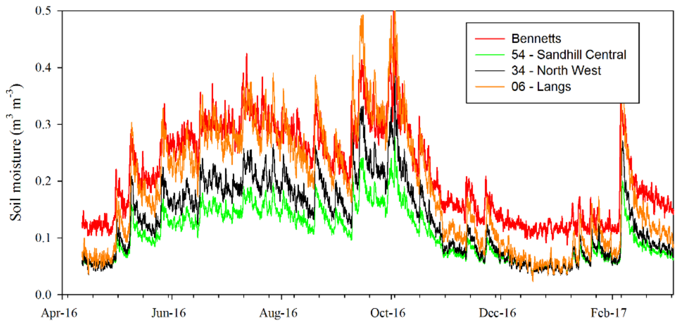

Figure 10. Time series of average soil moisture for selected properties in the intensive scale survey area and corresponding soil moisture time series from the Bennetts cosmic-ray soil moisture sensor. Scaling relations ships are provided in Table A1.

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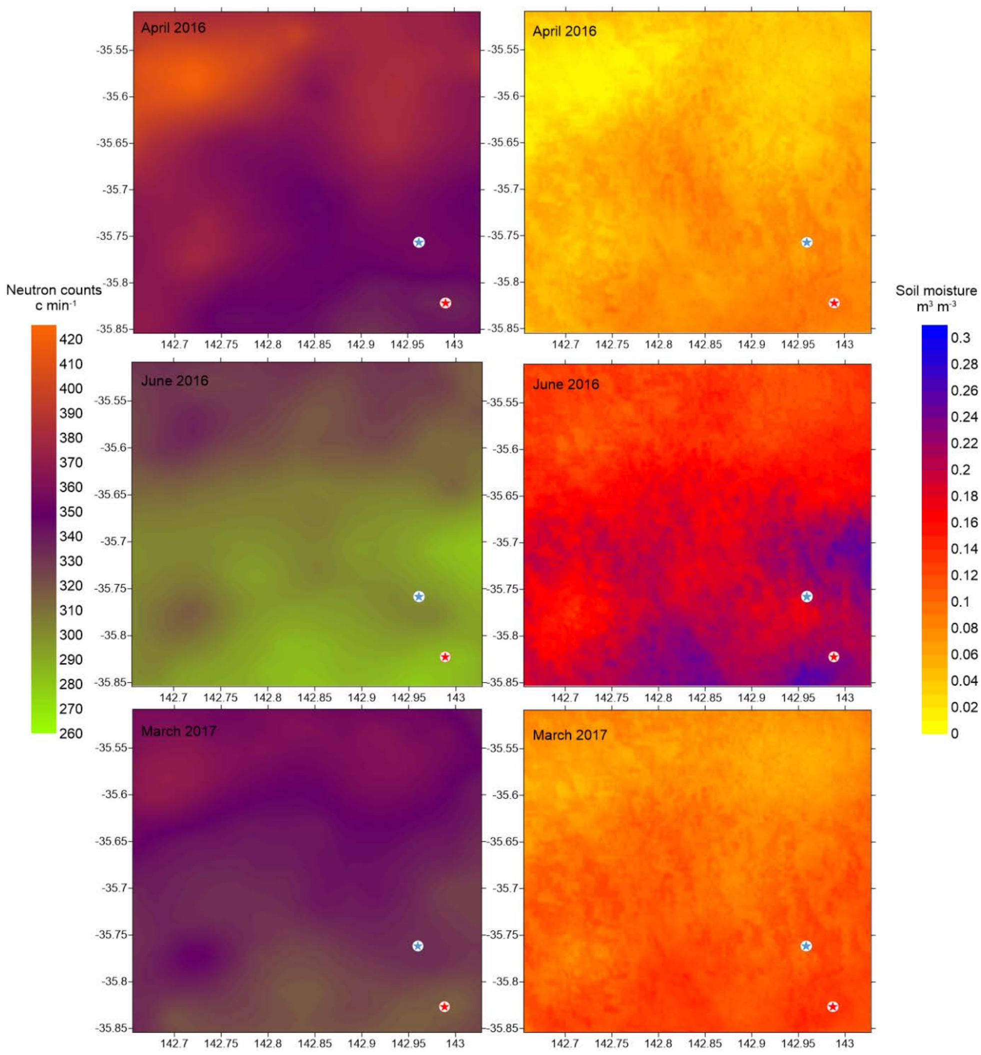

575

576 **Figure 11. Interpolated counts (left column) and derived soil moisture (right column) for the three broad scale**
577 **surveys during April 2016, June 2016 and March 2017. Blue and red stars indicate the location of the Bishes and**
578 **Bennetts cosmic-ray soil moisture sensors.**

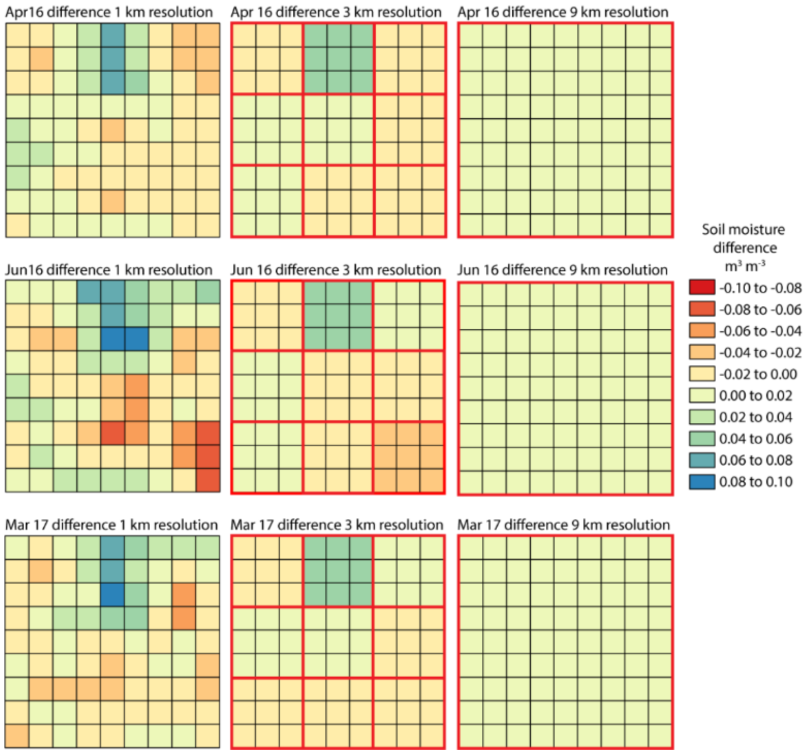

Figure 12. Difference in soil moisture estimates between the broad and intensive scale surveys for different resolutions on each of the three survey dates. Each cell represents a 1 km x 1 km region within the intensive survey zone.

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8 Appendix 1

Table A1. Supplementary information from regression analysis relating CRNS observations to property average soil moisture content in the intensive scale survey zone.

Property	Soil Moisture ($m^3 m^{-3}$)			Regression modelling results		
	Apr-16	**Jun-16**	**Mar-17**	**Slope**	**Intercept**	R^2
Bennetts CRNS	*0.124*	*0.277*	*0.157*			
54 - Sandhill Central	0.065	0.152	0.080	0.575	-0.008	0.999
26 - Whirily	0.103	0.294	0.140	1.257	-0.055	1.000
34 - North West	0.070	0.199	0.095	0.848	-0.036	0.999
09 - Bennetts	0.097	0.264	0.139	1.076	-0.034	0.998
21 - Arnolds	0.079	0.216	0.147	0.809	-0.003	0.905
25 - School	0.082	0.222	0.136	0.858	-0.013	0.968
17 - Jil Jil East	0.077	0.181	0.097	0.685	-0.009	0.999
14 - Sandhill South	0.074	0.202	0.104	0.828	-0.027	1.000
24 - Box	0.079	0.223	0.118	0.922	-0.032	0.997
29 - Hancocks	0.086	0.210	0.139	0.749	0.006	0.947
13 - Billabong	0.092	0.254	0.128	1.052	-0.038	1.000
38 - 30 Acre	0.081	0.187	0.106	0.688	-0.003	1.000
18 - Barley	0.105	0.227	0.141	0.777	0.013	0.992
16 - Bishes East	0.027	0.132	0.057	0.674	-0.053	0.995
08 - Connelly's	0.093	0.223	0.123	0.845	-0.011	1.000
11 - South McKenzies	0.106	0.261	0.144	1.003	-0.016	0.999
32 - Far West	0.063	0.192	0.124	0.765	-0.016	0.919
36 - Bishes West	0.043	0.166	0.091	0.754	-0.040	0.962
40 - Watsons	0.092	0.222	0.125	0.839	-0.009	0.998
50 - Hogans	0.087	0.236	0.127	0.957	-0.028	0.996
51 - Hennessy's	0.089	0.254	0.159	1.000	-0.019	0.947
23 - O'Keefes	0.062	0.187	0.099	0.793	-0.031	0.992
22 - Alfies	0.071	0.197	0.108	0.801	-0.024	0.993
15 - Sandhill North	0.045	0.122	0.063	0.504	-0.017	0.999
35 - Jil Jil West	0.057	0.164	0.072	0.721	-0.036	0.995
30 - Hancocks Hill	0.054	0.188	0.128	0.770	-0.020	0.865
04 - Biggses	0.097	0.242	0.153	0.891	-0.002	0.964
41 - Front	0.095	0.193	0.127	0.620	0.023	0.985
03 - Perns	0.076	0.213	0.135	0.827	-0.013	0.945
45 - Dip	0.095	0.213	0.135	0.734	0.011	0.982
06 - Langs	0.091	0.290	0.125	1.316	-0.076	0.998
07 - Spittles	0.094	0.275	0.119	1.216	-0.063	0.993
05 - Rogers	0.084	0.224	0.121	0.896	-0.024	0.997
19 - Clovers East	0.095	0.274	0.170	1.093	-0.024	0.951
10 - Caldoes	0.081	0.205	0.129	0.758	-0.003	0.965
12 - North McKenzies	0.089	0.269	0.140	1.149	-0.048	0.995
27 - Jack Shehans	0.083	0.216	0.135	0.818	-0.007	0.966
42 - Warne	0.066	0.189	0.089	0.807	-0.035	0.999
44 - Windmill	0.077	0.220	0.147	0.848	-0.010	0.911
43 - Top	0.074	0.206	0.093	0.883	-0.040	0.995
37 - Barrell	0.095	0.206	0.129	0.701	0.013	0.991
48 - Vernies	0.082	0.200	0.103	0.781	-0.017	0.999
20 - Clovers South	0.086	0.221	0.139	0.830	-0.006	0.963
33 - Near West	0.067	0.206	0.106	0.889	-0.039	0.995
31 - Back Jack Shehans	0.070	0.215	0.125	0.896	-0.030	0.969
28 - Clovers West	0.093	0.260	0.166	1.004	-0.014	0.940
39 - Crossroads	0.077	0.214	0.126	0.855	-0.020	0.977
53 - Clovers North	0.079	0.229	0.151	0.893	-0.013	0.917