Interactive comment on "Multiscale soil moisture estimates using static and roving cosmic-ray soil moisture sensors" by David McJannet et al.

Anonymous Referee #1

Received and published: 28 July 2017

The work presented by MacJannet and others investigates the use of mobile cosmic ray sensors for estimating soil moisture at a range of scales within a 36 km by 36 km area over an arid region in Australia. There are two regions of interest in the analysis, the 36 km x 36 km region aimed at producing 9km resolution soil moisture maps, and an inner region of 10 km x 10 km aimed at producing 1 km resolution soil moisture estimates. The authors highlight the importance of multi-scale soil moisture estimates for remote sensing validation as well as its use along with high-resolution land surface modeling.

The manuscript is concise and well written with clear steps. The figures are appropriate for the tasks taken and discussed in the manuscript. However, my main issue with this manuscript is its lack of novelty. The use of mobile cosmic-ray sensors (i.e., "rover") for soil moisture estimates is not new (as pointed out by the authors). The steps taken to convert the neutron counting rates from the rover to the final soil moisture is not new either. The regression analysis done to increase temporal resolution at gridded points within the region has also been done elsewhere. The manuscript reads very much like a technical report in which results are simply reported without much discussion. I don't see a clear scientific question being tackled in this manuscript. Perhaps, the only two pieces of relatively new information I noted were the updated relationship between lattice water and clay content particular applied to their region of interest (in comparison to a previous estimate from Australia) and the impact of number of integration points per area (which is directly related to the speed at which rover surveys are taken) on the quality of the soil moisture maps estimated from coarser to higher resolutions (but refer to my point about this below).

The authors made an important link to remote sensing soil moisture products and land surface modeling, and the manuscript feels a bit incomplete without a proper comparison against additional soil moisture "products". In addition, the authors claimed that the produced maps are "reliable" but how to assess reliability without an independent set of data? I strongly believe an independent set of data and comparison against model and remote sensing could have been an important addition to this manuscript and certainly contributing to its novelty. Unfortunately, I don't see a novel contribution that merits publication in HESS at this stage. My recommendation is for the authors to resubmit the work with a much clearer research question as well as incorporating of other independent soil moisture estimates to verify the impact of the rover soil moisture.

RESPONSE: In response to the reviewer comments we have now made major changes and compared distributed gravimetric point samples from each survey to rover results for both the intensive and broad scale products. We have also compared rover survey results at intensive and broad scale against distributed point samples and 5 km resolution water balance model estimates of soil moisture. For this analysis we have used the recently operationalised Australian Bureau of Metrology water balance model estimates of root zone soil moisture. Comparison to remote sensing and newly developed 1km model estimates is in preparation but are not feasible. This paper is about establishing correct experimental design, developing new approaches to provision of spatial soil properties, nesting surveys to test resolution and survey design and exploring temporal stability in soil moisture across scales. The reliability in measurements now comes from comparison of results to 5km

resolution water balance estimates, comparison to distributed gravimetric samples, successful calibration of the static and rover sensors and the fact that we can replicate the measurements across time. This is a data poor location the purpose of proposing the rover surveys is to produce much better soil moisture information into the future. This paper represent the first steps in the process.With the new data comparison that have now been added we strongly believe there are enough contributions to make this a stand-alone paper. This paper now has a number of novel contributions:

1. We demonstrate that the rover surveys compare well to grab samples and 5km resolution model results across both intensive and broad scale surveys.
2. We have develop a clay to lattice water relationship which is very strong. This growing data base of lattice water to clay relationships has also enabled us to produce a new lattice water product using the Australian Soil and Landscape Grid. This has potential application across Australia and internationally.
3. Our rover study is the first to use a digital soil mapping product to account for the spatial variation in soil properties across the survey area. This facilitate an easier set of data processing procedures and minimised assumptions that are made in other rover studies. This approach will be key to stream-lining the processing of spatial rover data in future surveys. This is a new approach to convert the neutron counting rates from the rover to the final soil moisture which can be applied to other gridded soil property databases.
4. We are the first study to use a nested high resolution survey within a larger broad scale survey. This approach has enabled us to test our experimental design in particular our selected driving speed and desired product resolution. This comparison has highlighted the need to design surveys fit for purpose and shows that different kriging models are required for different scale surveys as they are sensitive to different spatial information.
5. We have further demonstrated that N0 for static probes is strongly controlled by biomass. Our two static sites with different soil type and moisture have essentially the same N0 as the respective footprints are essentially biomass free. This is very useful information for rover surveys in this region and points to a standard N0 if biomass is accounted for in calibration and spatial variation in incoming neutron intensity can be correctly accounted for.
6. We have provided evidence for temporal stability in soil moisture in this dry land setting. We demonstrate this at the property scale (most relevant to farm managers) and this has great relevance to local land holders who can relate their property to neighbouring sensors, and scientists who can use point-to-area scaling to fill the gaps between rover surveys for comparison to other soil moisture products.

These points will all be described in our modified discussion section.

Additional specific comments:

1. Eq. 5: Please, explain what W_lat, W_SOC, and rho_bd are right after the equation is presented. I believe rho_bd is never described properly in the text.

RESPONSE: Fixed as suggested and rho_bd description added

2. Section 2.3: It might be a good idea for the authors to show a picture of the rover system in this section.

RESPONSE: We have pictures on our cosmoz website (http://cosmoz.csiro.au/about-cosmoz/) so we will add a link to these rather than making the manuscript any larger

3. Section 3.1: I believe Fig 4 is meant to be mentioned in this section (but it is not currently)

RESPONSE: Fixed

4. Section 3.3: I believe Fig 5 is meant to be mentioned in this section (but it is not currently)

RESPONSE: Fixed

5. Section 3.4 and 3.5: The authors assume the reader has good knowledge of spatial statistics and how the fields are ultimately interpolated to produce soil moisture maps. For example, the discussion about "sill" may not be clear to the broad readership of HESS. In fact, what does having or not having a "sill" imply? What does "sill" represent in this case (from a physical soil moisture variability context)? The authors should also highlight the sill parameter in the plots presented in Fig 6.

RESPONSE: The concept of the sill and what it means for spatial statistics has been added to section 3.4. The meaning of the sill and range in the context of spatial interpolation has been added. The sill and range are labelled in fig 6 to aid interpretation as suggested by the reviewer

6. Section 3.5: Ideally, one (including myself) would like to see the soil moisture maps compared against independent measurements. It is expected that the map-derived soil moisture will compare well with the two static sites since the rover was calibrated using the same data. So, the whole approach appears a bit "circular" to me. At the end of this section, the authors make a good point about the importance of these measurements form model testing and remote sensing. I strongly recommend the authors to expand their manuscript to include comparison against remote sensing and land surface mode and discuss reasons for similarities and differences.

RESPONSE: In response to the reviewer comments we have now made major changes and compared distributed gravimetric point samples from each survey to rover results for both the intensive and broad scale products (fig 9 and 13). We have also compared rover survey results at intensive and broad scale against distributed point samples and 5 km resolution water balance model estimates of soil moisture. For this analysis we have used the recently operationalised Australian Bureau of Metrology water balance model estimates of root zone soil moisture. In addition, we note that in the existing analysis we are not comparing the non-moving rover to the static sensors – this is the final interpolated soil moisture product using the soil grid properties and conventional kriging of neutron counts. We are testing the whole calculation procedure and underlying data (i.e. soil properties) here. We are comparing to static sensor which uses locally measured soil properties. The results here would only be expected to be this good if the spatial interpolation models used were accurate. Comparison to remote sensing and newly developed 1km model estimates is in preparation.

7. L290-302: There is some potentially interesting analysis here but I also wonder if the results can be strongly influence by the soil properties themselves. In other words, if the authors apply the same comparison between the broad survey and intensive survey using the soil properties (not the estimated soil moisture), would they see a similar behaviour? How much of the difference in soil moisture they currently observed is conditioned to the soil properties versus the changes in resolution due to averaging? Also, how can the authors justify comparing measurements, despite being originally taken at different resolution, that essentially come from the same methodology, instrument, and calibration against the same data? This appears a bit weak to me and reinforces my point about differences due to variation in soil properties.

RESPONSE: We cannot produce the same plots of difference (as with soil moisture, i.e. Fig12) as the same underlying soil property data is used from the Australian soil and Landscape grid for both surveys and its resolution is 90 m. The differences between surveys observed in Fig 12 are purely those related to differences in neutron counts in both surveys which were observed at very different speed. The broad survey is moving so fast the small scale detail is smoothed out hence the difference at the 1 km and 3km scale but none at 9km scale. We justify comparing the measurements as we are demonstrating the importance of selecting the appropriate drive speed depending on the final product resolution required. We show that the speeds used for the broad scale survey are not suitable for soil moisture estimates at resolutions of 1 km and 3 km. We only get agreement between the two products when the resolution is set at 9km – i.e. the design speed has been successfully set.

8. L329-342: Interesting discussion about the road effect. It can definitely influence the results but I'd expect such influence to be more pronounced in humid sites (and not so much at arid sites)??? Also, because the maps (broad and intensive surveys) are derived from the same approach, any road effect may actually be cancelled out when comparing both surveys.

RESPONSE: The issues of road influences is definitely an interesting one and is something future surveys should take into account. I am aware of some researchers who are working on a solution to this issue (not published yet) and as you say this will be particularly useful in wetter/more humid areas. To push this fact further more text will be added to highlight that the dry road will be over represented in the measured neutron intensity as the sensitivity to hydrogen of neutron intensity is greater at the dry end. Inputs from Martin Schron in the online discussion have been very useful in addressing this.

9. Table 1: Please, add a column with footprint-average soil moisture conditions for each case

RESPONSE: This information has been added to Table 1

10. Figure 7: These maps are interesting but they should be evaluated with other points (any points available within the domain) that had not been directly used to calibrate the rover itself. Otherwise, the only information in those maps are potentially the relative differences between wet and dry areas. Similar comment applies to Figs 9, 10, and 11.

RESPONSE: In response to the reviewer comments we have now made major changes and compared distributed gravimetric point samples from each survey to rover results for both the intensive and broad scale products (2 new figures). We have also compared rover survey results at intensive and broad scale against distributed point samples and 5 km resolution water balance model estimates of soil moisture. For this analysis we have used the recently operationalised Australian Bureau of Metrology water balance model estimates of root zone soil moisture.

11. Figure 8: The results here are expected and my only interpretation here is that the characteristics of soil moisture at 1km resolution (obtained with the rover) are comparable to finer scale from the static sensor (i.e., there may not be large differences between the 200-300m integrated soil moisture compared to the 1km resolution product).

RESPONSE: The results here would only be expected to be this good if the spatial interpolation models used were accurate. We are not comparing the non-moving rover to the

static sensors – this is the final interpolated soil moisture product using the soil grid properties and conventional kriging of neutron counts. We are comparing to static sensor which uses locally measured soil properties.

12. Figure 12: For all soil property maps in the domain (W_lat, W_SOC, rho_bd), can the authors reproduce the same plots? In other words, averages at 1km, 3km, and 9km within the overlapped area for broad and intensive surveys. Can the results tell authors what possible controlling factors are associated with the differences between both surveys? I believe this can initially be expanded to something interesting and novel.

RESPONSE: As for comment 7 above - We cannot produce the same plots of difference (as with soil moisture, i.e. Fig12) as the same underlying soil property data is used from the Australian soil and Landscape grid for both surveys and its resolution is 90 m. The differences observed in Fig 12 are purely those related to differences in neutron counts in both surveys which were observed at very different speed. The broad survey is moving so fast the small scale detail is smoothed out hence the difference at the 1 km and 3km scale but none at 9km scale.

Interactive comment on "Multiscale soil moisture estimates using static and roving cosmic-ray soil moisture sensors" by David McJannet et al.

REPLY TO REVIEWER 2 COMMENTS 09/08/2017

Anonymous Referee #2

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The authors present a nice and straight forward multiscale soil moisture experiment in Australia using the relatively new cosmic-ray neutron rover. While the experiment has been performed in Hawaii, Arizona, Oklahoma, and Nebraska, the study does break some new and interesting ground related to the technology and its application. The authors find an excellent relationship between clay percent and lattice water, which is a critical second order effect on the conversion of neutron counts to soil moisture. In addition, the authors nicely illustrate the challenges and solutions to designing a multiscale soil moisture experiment. The rover counts and survey speed should be tailored to the scale of soil moisture heterogeneity present and desired scale results of the experiment. Given the need for more and better soil moisture validation datasets for satellite estimates of soil moisture this is an important methodology paper illustrating the utility of the rover to meet these needs. Lastly the authors present an interesting scaling approach for obtaining point to area averages. This is critical for making soil moisture observations more useful for land management applications which often involve complex areas and are poorly represented by both point sensors and satellite products. The paper is well organized, straight forward, and appropriate for HESS.

Attached are a few key points to address.

1. The authors point to area regressions are based on 3 rover surveys only. While I understand the challenge of collecting multi-date information the authors should mention this limitation. In particular future work should perform a leave one out cross validation study in order to properly identify the error of the point to area methodology and temporal stability of soil moisture patterns. I think a description of this need for future work should be discussed more clearly as a limitation of the study. However, I am confident that the cross validation error would be fairly small and not affect the overall conclusions of the paper.

RESPONSE: This limitation is now clearly identified and, as suggested by the reviewer a recommendation for replication and further testing has been added to the discussion. We agree that the cross validation will likely show only small errors but this discussion is included anyway.

2. Page 2 L 43. The authors should see Andreasen 2016 and 2017 for a better description of the moderated detector energy bins.

Andreasen, M., K. H. Jensen, M. Zreda, D. Desilets, H. Bogena, and M. C. Looms (2016), Modeling cosmic ray neutron field measurements, Water Resources Research,

52(8), 6451-6471. doi:10.1002/2015wr018236.

Andreasen, M., K. H. Jensen, D. Desilets, T. E. Franz, M. Zreda, H. Bogena, and M. C. Looms (In press 2017), Status and perspectives of the cosmic-ray neutron method for soil moisture estimation and other environmental science applications Vadose Zone Journal.

RESPONSE: A better description of the energy bins detected by the CRNS has now been included and the relevant references have been included as suggested

3. Page 8 L 273. The high R^2 values are due to the few number of surveys performed. A cross validation experiment would be better suited to address error in future rover work. Authors should mention number of sample points here and in the discussion.

RESPONSE: New text highlighting the limitations of three data points has now been added to the results and discussion section to make this clear to the reader.

4. Figure 9. The authors should use the same scale as Fig. 7. Odd visual that wetter spots are more red instead

RESPONSE: Figure 9 has been revised and now uses the same colour scale as Fig 7 for consistency. The wet blue colour from fig 7 scale does not appear as the soils are too dry.

Review of the paper: "Multiscale soil moisture estimates using static and roving cosmic-ray soil moisture sensors"

by: David McJannet

GENERAL COMMENTS

The paper describes a research project aimed at producing soil moisture estimates at a range of scales that are commensurate with model and satellite retrievals. The study involved static cosmic ray neutron sensors and rover surveys across both broad (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.

Given the ever increasing lack of ground measurements, having medium-to-high resolution observations of soil moisture against which validating satellite soil moisture products is extremely important. With the advent of Sentinel 1 satellite sensor we will have soon soil moisture estimates at 1 km of resolution or even lower. Hence, studies involving any technique for retrieving or expand the availability of these information are very welcome in literature. For this reason, I think the topic is of interest for the journal readership and worth the consideration for the publishing in HESS journal. The paper is also well written and structured and concise at point.

My main recommendation for the authors is to put more effort to underline the real merit of the paper by trying to underline the differences with respect to previous studies and add material that makes the study more close to a scientific paper than a technical report. Indeed, I struggled a bit to grasp the novelty and potentiality of the study – "The paper describes a research project" as written by the authors in the abstract – and this does not do justice to the merit of the study. My suggestion is to provide a comparison of the rover estimates with a model or other types of observations (like the gravimetric measurements the authors have collected) demonstrating the reliability of the rover estimates in terms of reproducing spatial pattern of soil moisture which can be extremely useful for validating high-resolution satellite soil moisture products.

RESPONSE: In response to the reviewer comments we have now made major changes and compared distributed gravimetric point samples from each survey to rover results for both the intensive and broad scale products. We have also compared rover survey results at intensive and broad scale against distributed point samples and 5 km resolution water balance model estimates of soil moisture. For this analysis we have used the recently operationalised Australian Bureau of Metrology water balance model estimates of root zone soil moisture. In addition to this we also believe that the components of this paper that make it novel include; 1) our newly developed clay to lattice water relationship which we apply to nationally available soil property grid for Australia, 2) use of digital soil mapping products to account for the spatial variation in soil properties across the survey area and facilitate data processing, 3) presenting results of a nested high resolution survey within a larger broad scale survey which enabled us to test our experimental/driving speed design, 4) providing further evidence that N0 for static probes is strongly controlled by biomass, and 5) demonstrating temporal stability in soil moisture in this dry land setting. Significant rewording and new text and figures has been added throughout.

I also have other comments the authors can be considered to improve the manuscript. I report below my comments in order of appearance indicating also their relevance. (COMMENTS REMOVED FROM TABLE FOR RESPONSE):

Page3, Line 102, Minor: Define fp here. Cosmic-ray neutron intensity, fp, is part….

RESPONSE: Fixed

Page 5, Line 155, Minor: 18 time..faster?

RESPONSE: Reworded to "The rover has counting rates approximately 18 times greater than that of a standard static sensor under the same condition, thus, allowing for measurements to be made at one minute intervals."

Page 7, Section 3.2 and 3.3, Moderate Figures 4 and 5 not cited in text

RESPONSE: Fixed

Page 7, Section 3.5 Intensive scale rover survey, Moderate, I think it is too much optimistic to say that the agreement is excellent based on only on two points and three times. Why not comparing spatially with model estimates?

RESPONSE: We have now introduced two independent data sets to assess the rover performance and this has been a major change to the paper. These independent measures are distributed gravimetric point samples collected during each survey and estimates from the recently operationalised bureau of meteorology water balance model (5km resolution) estimates of root zone soil moisture. These two independent products are compared against both the intensive and broad scale results to demonstrate. Two new figures have been added results new text has been added to results and discussion sections.

Page 8, Line 264-277, Moderate/Major, Provide more details about the point-area regression analysis. It is not completely clear from the text.

RESPONSE: this section has been reworded for clarity and the need for future surveys to improve these relationships has been added.

Page 16, Figure 1, Minor, Provide scale of the figure and indication of the size of the box.

RESPONSE: Scale now added to zoom in area. Box dimensions added to caption too.

Based on the comments above I recommend the publication after MODERATE/MAJOR REVISIONS.

Interactive comment on "Multiscale soil moisture estimates using static and roving cosmic-ray soil moisture sensors" by David McJannet et al.

R. Baatz (Referee) r.baatz@fz-juelich.de

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General Comments:

The manuscript nicely describes a blueprint for a roving cosmic ray neutron sensor application (CNRS) for remote sensing validations, land surface model validation, and field scale soil moisture retrieval over adequately large farmlands. Conditions for application, and guidelines are outlined in sufficient technical depth. The novelty of this manuscript is the clear presentation of the technical methodology, focus on the purpose, conclusiveness of the experiment and validation of the derived data by static and additional roving CRNS experiments. Hence, the manuscript deserves to be published in HESS subject to revisions which can be easily handled by the authors.

Specific and technical comments:

There are few points which will improve the quality of the paper mostly regarding restructuring of the text and improving clarity of the figures. Although methods and results are mixed at several instances, the manuscript was written fluently and well readable, containing the necessary technical details and contents for reproducible. Along with restructuring, novelties might be marked more strikingly by additional sub headings.

l 42: scale hectometers - rephrase

RESPONSE: Fixed

l 46: remove "better" otherwise better than what?

RESPONSE: Fixed

l 48: I'd suggest to treat land surface modeling separate to remote sensing, and include parameter estimation studies which actually use CRNS already (and are potential cases for rover application at horizontal scale) such as Baatz et al. 2017 "improved land surface model prediction" and Villarreyes et al. 2014 "Inverse modelling of cosmicray..." .

RESPONSE: We now treat remote sensing, land surface modelling and parameter estimation studies separately and have included those citations as suggested.

l 83: indicate time over which is averaged (monthly average or daily average)

RESPONSE: the time period is daily - fixed

l 86: Stick to one terminology. The authors switch repeatedly between CRNS (this one should be preferred), "cosmic ray soil moisture sensor" and many others throughout the manuscript and headings.

RESPONSE: will now use preferred option

l 93: add citation (e.g. Hawdon et al.)

RESPONSE: added as suggested

l 131: isn't air pressure (fp) used to scale to sea level (1013 hPa) instead of an additional scaling factor (fs)? This would avoid using a redundant scaling factor fs.

RESPONSE: In our case a reference level for fp of sea level is used so in this case the fs is redundant – we leave it in as it may be used in other studies if a different reference elevation is used for air pressure correction (e.g. site average Pressure).

l 152: This sub-chapter can be restructured mostly to include sections from "Results" but which actually are "Methods". Here, the novelties and blueprint character could be more concise.

RESPONSE: Many changes made and all method texts now moved to the methods section as suggested.

l 187: This is not an "additional" part. Now, it is part of this study.

RESPONSE: correct – reworded

l 197: This is very likely the approach taken by Baatz et al. "An empirical veg.." Eq. 2.

RESPONSE: citation added and new text included

l 209-210: Move to methods

RESPONSE: Shifted to methods as suggested

l 214-217: What is remarkable similar? Just the results should be clear enough. Here, the curve-average resulting difference in soil moisture should be also noted, since this is the variable of interest for hydrologists. As it reads now: The interpretation would be that biomass pools are equal. Perhaps, knowing the site conditions, biomass "is basically non-existent".

RESPONSE: Removed remarkable and reworded. Added the average soil moisture difference to.

L 219-221: Move to methods. Paragraph reads like the approach described in Baatz et al. 2015.

RESPONSE: This reference has been included now

l 228-232: Move to methods.

RESPONSE: removed from results and covered in methods

l 232-233: This is a result.

RESPONSE: agree

l 233-235: Move to methods.

RESPONSE: Have left this here with revised wording as the new lattice water product is a result of this study and the result loses its context if this is not included

l 249-251: Move to methods or rephrase.

RESPONSE: removed – scale issue covered in methods

l 259: Please investigate.

RESPONSE: we have no way to investigate these differences we can only speculate as to the difference based on local observations. Any point in the rover survey is interpolated using a number of neighbouring points based on the variogram relationships – if there is a very abrupt change in counts in an area it will be smoothed by such an approach.

l264: "farm property" seems a key words and should be introduced earlier.

RESPONSE: The concept of farm property and the scale of these is now introduced in the methods

l 267-272: Move to methods.

RESPONSE: Moved as suggested

l 275-277: Move to after-results e.g. conclusion or outlook.

RESPONSE: Moved to discussion section

l 290ff: to methods.

RESPONSE: Moved to methods

l 295-299: Link/relate results to driving speed and counting rates.

RESPONSE: Link between driving speed, sample points and counting rates now made clearly

l 320: replace will with with

RESPONSE: Fixed

Fig. 1: Insert Map of Australia and consider landscape format of the figure.

RESPONSE: Map of Australia now added and landscape format used

Fig. 2 and others: Add axis title (Lat/Lon).

RESPONSE: Lat long added to Fig 2, 3, 7, 10 and 12

Fig. 3: Consider using color bars with 2 colors for b, c, and d. "m ASL" was used in the text, so please use it in the figure as well. Now it is "m AHD".

RESPONSE: Colour bars with two colours now used for b,c and d. Changed to m ASL to be consistent with text. Also added LAt/long

Fig. 7 and 11: Consider dark Brown- light Yellow or other color bars with 2 colors for neutron counts. Is this already corrected neutron counts? This would be desirable, please indicate. Soil moisture is preferably shown with red-green-blue color bar throughout all plots. The counts shown should be corrected neutron counts. Otherwise, the additional value is not clear. Why are the interpolation patterns for neutron counts not visible in the soil moisture interpolations? I suggest to coarsen the visual representation.

RESPONSE: Dark brown to Yellow is now used throughout for neutron count maps. The neurons are 'corrected' and this has now been made clear in moth figure captions and in the figure itself. Soil moisture is now presented as Red-Green-Blue as suggested in plots 7, and 11 (now 12). The interpolation patterns as the neutron counts are interpolated but are then multiplied by the 90m resolution soil grid data. We have made a point throughout to point put the intended resolution of the intensive and broad-scale surveys.

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 methods, results and testing of ~~a research project aimed at producing~~ soil moisture estimates produced using rover surveys 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. We use independent gravimetric and modelled soil moisture estimates collected across both space and time to validate rover soil moisture products. 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

38 traditional in situ sensors which creates an issue because of the well documented small scale variability in soil

39 moisture (Vereecken et al., 2014; Western and Blöschl, 1999). Some researchers have overcome this issue by

40 establishing soil moisture monitoring networks (Bogena et al., 2010; Smith et al., 2012), but the extent of sensor

41 networks is still relatively small (<1 km^2).

42

43 More recently cosmic-ray neutron sensors (CRNS) have been deployed to provide soil moisture estimates at

44 ~~a~~the ~~scale~~ hectometre scales (circular footprint, 260-600 m diameter) (Desilets and Zreda, 2013; Köhli et al.,

45 2015). CRNS sensors measure naturally generated ~~fast~~ neutrons ~~(energy 10–1000 eV)~~ that are produced by

46 cosmic rays passing through the Earth's atmosphere. Recent measurement and modelling studies (Andreasen et

47 al., 2017a; Andreasen et al., 2017b) have shown that the CRNS sensors measure neutrons in both the thermal

48 (<1 eV) and epithermal ranges (>1 - 1000 eV) and that sensitivities to energy range vary with environmental

49 features present at a site (e.g. tree canopy, crop, litter). The neutron intensity above the soil surface is inversely

50 correlated with soil moisture as it responds to the hydrogen contained in the soil and plant water and to a lesser

51 degree to plant and soil carbon compounds (Desilets et al., 2010). The ~~better~~ scale match between the CRNS

52 technique and satellite observations has led to a number of recent studies which compare CRNS observations to

53 satellite observations (Renzullo et al., 2014; Montzka et al., 2017; Kędzior and Zawadzki, 2016)~~.~~ and land

54 surface models (Vinodkumar et al., 2017; Holgate et al., 2016), and use CRNS observation to parameterise

55 models (Baatz et al., 2017; Rivera Villarreyes et al., 2014).~~and modelled soil moisture~~ Development of networks

56 of CRNS across a number of countries (e.g. USA (Zreda et al., 2012), UK (Evans et al., 2016), Germany (Baatz

57 et al., 2014), and Australia (Hawdon et al., 2014)) is providing useful time series of soil moisture information

58 which will be valuable for years to come.

59

60 While the CRNS provides a better match to the scale of satellite retrievals and model estimates there is still a

61 scale mismatch that prevents direct full-scale validation of these products. To address this, a mobile CRNS,

62 called the cosmic-ray rover has been developed (Desilets et al., 2010). The rover uses the same technology as

63 the CRNS but its design allows for mobile mapping of soil moisture across the landscape. This mobile mapping

64 capability allows for soil moisture surveys to be undertaken over areas commensurate with satellite pixels or

65 model domains thereby filling the gap in soil moisture observations (Chrisman and Zreda, 2013). The earliest

66 use of the cosmic-ray rover was for repeated surveys across an area of 25 x 40 km in the Tucson Basin in order

67 to produce a catchment scale water balance (Chrisman and Zreda, 2013). Dong et al. (2014) used a rover to map

68 soil moisture on multiple occasions over a 16 x 10 km and a 34 x 14 km region in Oklahoma with the aim of

69 evaluating satellite soil moisture estimates. More recently Franz et al. (2015) combined rover surveys over a 12

70 x 12 km area in Nebraska with CRNS measurements to develop a technique for multiscale real-time soil

71 moisture monitoring.

72

73 This paper describes part of a research project aimed at producing soil moisture estimates at a range of scales for

74 eventual comparison to satellite and modelled soil moisture estimates. The focus of this paper is on establishing

75 techniques for producing spatial representations of soil moisture using CRNS sensors and a cosmic-ray rover.

76 We will present a nested set of broad scale and intensive scale rover survey results which were collected across

77 a 36 x 36 km area in a cropping district in Mallee region of Victoria, Australia and we will describe techniques

78 used to convert rover measurements into soil moisture estimates using CRNS sensors and spatial soil property

79 information. Using statistical relationships between property scale soil moisture from rover surveys and CRNS

80 sensors we will present a simple approach for producing real-time property-scale soil moisture estimates in the

81 local area. We also use our observations at different scales to test the reliability of our experimental design.

82 2 Methods

83 2.1 Site description

84 The study area is located in the Shire of Buloke in the Mallee region of Victoria, Australia (Figure 1Figure 1).

85 The measurement campaign took place across a 36 x 36 km region centred on -35.684°S, 142.858°E, which lies

86 between the towns of Birchip to the south and Sea Lake to the north. The Mallee is a rain fed agricultural region

87 with wheat and barley being widely grown. Much of the native vegetation has been removed since European

88 settlement. In the region of interest the landscape is flat with an elevation ranging between 50 to 120 m ASL.

89 The climate of the area is classified as semi-arid with an average annual rainfall of 368 mm, an average daily

90 minimum temperature in July of 3.6°C and an average daily maximum temperature in January of 30.7°C

91 (Anwar et al., 2007).

92 2.2 Static cosmic-ray soil moistureneutron sensors

93 Cosmic-ray soil moistureneutron sensors were installed at two locations in the designated field survey area

94 (Figure 1Figure 1). These two locations are named Bishes (northern probe) and Bennetts (southern probe). Each

95 of these sensors included a single polyethylene shielded cosmic-ray probe (CRP-1000B, Hydroinnova,

96 Albuquerque, USA), which monitors neutron intensity in the epithermal to fast neutron energy range. Each

97 system also measured barometric pressure, temperature and relative humidity, which are required for

98 measurement correction procedures. The system was programmed to record data at hourly intervals and was

99 sent via satellite telemetry (Iridium SBD services) in near-real-time to a database on a remote server

100 (cosmoz.csiro.au) (Hawdon et al., 2014). Prior to deployment, the two static sensors were run side-by-side for a

101 period of 4 days to determine if there were any differences in counting rates that were not attributable to local

102 conditions. Over this period the average counting rate differed by less than 1%, thus giving confidence that

103 differences between sensors reflect local site characteristics alone.

104

105 In order to isolate the effect of soil moisture on neutron count measurements it is first necessary to remove

106 variation due to other environmental factors. The largest correction that is required is an adjustment for changes

107 in atmospheric pressure, but there are also corrections required for changes in atmospheric water vapor and

108 changes in the intensity of the incoming neutron flux. The standard correction procedures implemented across

109 the CosmOz network have been described in detail by Hawdon et al. (2014) therefore only a brief summary will

110 be provided here.

111

112 Cosmic-ray neutron intensity- is particularly sensitive to elevation or the mass of air above the sensor, which is

113 accounted for by the by the correction factor , f_P , which is defined as an exponential relationship with

114 barometric pressure (Zreda et al., 2008);

115 $$f_P = \exp\left[\beta\left(P - P_{ref}\right)\right]$$ Eq. 1

116 where P is atmospheric pressure (mb) and P_{ref} is the reference atmospheric pressure (mb); which is calculated

117 using standard formulas based on site elevation (NASA, 1976). The atmospheric attenuation coefficient (β,

118 cm^2 g^{-1} or mb^{-1}) for neutron-generating cosmic rays has been calculated for each of our sites using the method

119 described by Desilets et al. (2006).

120

121 Water vapor in the atmosphere has the same neutron moderating capacity as water in the soil and as such will

122 influence the total neutron count (Zreda et al., 2012). A correction factor for atmospheric water vapor effects

123 was developed by Rosolem et al. (2013) and it utilises near surface absolute humidity (ρ_{v0} , g m^{-3}), which is

124 derived from measurements of temperature, atmospheric pressure and humidity. The correction factor for

125 atmospheric water vapor (f_{wv}) is derived from;

126 $$f_{wv} = 1 + 0.0054\left(\rho_{v0} - \rho_{v0}^{ref}\right)$$ Eq. 2

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

128 To account for variations in incoming neutron flux an intensity correction factor is calculated by normalising the

129 source intensity to a fixed point in time (Zreda et al., 2012). The correction factor for incoming neutron intensity

130 (f_i) is expressed as;

131 $$f_i = \frac{I_m}{I_{ref}}$$ Eq. 3

132 where I_m is the selected neutron monitor counting rate at any particular point in time and I_{ref} is a reference

133 counting rate for the same neutron monitor from an arbitrary fixed point in time which is 1 May 2011. Neutron

134 monitor data is sourced from the Neutron Monitor Database (NMDB; www.nmdb.eu). Both of these sites utilise

135 data from the Lomnický štít Observatory in Slovakia.

136

137 The counting rate is also scaled to sea level and high latitude to enable comparison between sensors. Scaling

138 factors for converting counting rate to sea level (f_s) and high latitude (f_l) are described by Desilets and Zreda

139 (2003) and Desilets et al. (2006).

140

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

142 $$N = N_{raw}\left(\frac{f_P f_{wv}}{f_i}\right)\left(\frac{f_s}{f_l}\right)$$ Eq. 4

143 Where N_{raw} is the uncorrected neutron count from the CRP. Corrected neutron counts were converted to

144 volumetric soil moisture content (θ) using the calibration function generated by Desilets et al. (2010) and

145 modified by Bogena et al. (2013):

146 $$\theta = \left(\frac{0.0808}{\left(\frac{N}{N_0} \right) - 0.372} - 0.115 - w_{lat} - w_{SOM} \right) \rho_{bd}$$ Eq. 5

147 where N_0 is the neutron intensity in air above a dry soil which is obtained from field calibration, w_{lat} is lattice

148 water content of the soil, w_{SOM} is soil organic matter expressed as a water equivalent (see below), and ρ_{bd} is

149 bulk density of the soil.

150

151 Field calibration at each site involved collection of gravimetric and volumetric soil samples at three distances

152 from the probe (25m, 100m and 200m) along each cardinal and inter-cardinal direction (i.e. 8 radial directions).

153 At each sample point, soil cores were taken to calculate volumetric soil moisture content for three depths (0 to 5

154 cm, 10 to 15 cm, and 25 to 30 cm), giving a total of 72 samples per calibration. Water content from samples was

155 determined by drying samples at 105°C for 24 hours (Klute, 1986). The depth weighted soil moisture from field

156 calibration was calculated using the method proposed by (Franz et al., 2012) and corresponding corrected

157 neutron count is used to determine N_0 in Eq. 5. Hydrogen held within the lattice structure of the soil minerals

158 and organic material can also effect neutron count rate and, hence, need to be considered in calculation

159 procedures. Lattice water (w_{lat} -) was determined from the amount of water released at 1000°C preceded by

160 drying at 105°C. Soil organic carbon was estimated by measuring total organic carbon in samples using Heanes

161 wet oxidation, method 6B1 in Rayment and Higginson (1992). Following Franz et al. (2013) and Bogena et al.

162 (2013), the organic carbon was assumed to be present as cellulose, $C_6H_{10}O_5$, and this was converted into an

163 equivalent amount of water (w_{SOM}) by multiplying measured soil organic carbon by 0.556, which is the ratio of

164 five times the molecular weight of water to the molecular weight of cellulose.

165 **2.3 Rover system**

166 The rover system is based around a set of 16 custom made tube capsules supplied by Hydroinnova

167 (Albuquerque, USA), which are similar to those used for the static cosmic-ray soil moistureneutron tubes

168 sensors but larger. The rover has a counting rates approximately 18 times greater than that of a standard static

169 sensor under the same condition, thus, allowing for measurements to be made at one minute intervals. For a

170 volumetric soil moisture content of 10% a count rate of around 350 c min^{-1} was recorded. The set of 16 tubes is

171 mounted in a trailer from which additional measurements of air temperature, relative humidity, atmospheric

172 pressure and location were also made. Pictures of the rover system are available on the CosmOz webpage

173 (http://cosmoz.csiro.au/about-cosmoz/). While mobile, the measurements from the system were monitored in

174 real-time on a screen in the cabin of the tow vehicle. A dash mounted camera was also used to collect images at

175 one minute intervals during the survey.

176

177 For this investigation a nested design of broad scale and intensive localised measurements was implemented.

178 The broad scale design included a survey over an area with dimensions of approximately 36 x 36 km which

179 encapsulated a single Soil Moisture Active Passive (SMAP) satellite pixel. Using typical counting rates for this

180   area and by targeting an output resolution for soil moisture of 9 x 9 km we calculated that the maximum driving

181   speed for this survey was 90 km h^{-1}. This provided a good density of measurement points for interpolation

182   purposes. The survey area and measurement points from the driving track are shown in Figure 2. The broad

183   scale surveys typically took 10 h to complete, involved over 600 measurements and the average speed travelled

184   was around 60 km h^{-1}. The intensive scale survey covered an area of approximately 10 x 10 km and was located

185   in the south eastern corner of the broad scale survey (Figure 2). In this survey a target resolution for soil

186   moisture of 1 x 1 km was used for which we calculated that the maximum driving speed should not exceed 30

187   km h^{-1}. Much of the driving for the intensive scale surveys was around field boundaries and on unsealed roads.

188   At 1 km resolution the intensive scale survey results were well matched to farm property scale in this region.

189   Intensive scale surveys also took approximately 10 h to complete with more than 600 measurement point being

190   collected. The average speed during these surveys was 20 km h^{-1}. Survey tracks were defined for both surveys

191   prior to undertaking measurement using maps of the local road network. These maps were loaded into GIS

192   software and were used to guide navigation on each survey run.

193

194   The nested design of the intensive and broad scale surveys (Figure 2) enables the accuracy of broad scale survey

195   estimates to be assessed. To undertake such an analysis we selected a 9 x 9 km area within the area of survey

196   overlap (Figure 2) and derived corresponding soil moisture at resolutions of 1, 3 and 9 km. In such an analysis

197   the intensive survey results are considered as a point of truth for broad survey results.

198

199   As well as enabling production of direct farm property-scale estimates at the time of the surveys, the intensive

200   scale survey results were used to derive a much higher time resolution soil moisture product at the property

201   scale. This was achieved using spatial regression analysis with the continuous soil moisture measurements at the

202   static CRNS observations at Bennetts. Linear regression equations were derived for each property by comparing

203   the soil moisture content at the Bennetts CRNS versus the corresponding rover survey soil moisture for each

204   property in turn. Using this approach, regression relationships were developed between the Bennetts CRNS and

205   50 properties identified within the intensive survey area for the three surveys undertaken. These relationships

206   enable production of continuous farm property scale in this area. This approach assumes that rainfall is

207   relatively uniform across the region and that crops are planted across all periods; both of which are typical in

208   this study area.

209

210   Procedures used for correcting static cosmic-ray neutron sensor counts (Eq. 1 to Eq. 4) were also applied to the

211   rover data. Continually varying elevation, location, pressure, temperature and humidity were used for these

212   calculations. Soil moisture was also calculated in the same way as for the static sensors (Eq. 5) but there was a

213   requirement for spatial information regarding bulk density, soil organic matter and lattice water content. The

214   Soil and Landscape Grid of Australia provides ~90 x ~90 m pixels of digital soil attributes including bulk

215   density (Viscarra Rossel et al., 2014a) and soil organic carbon (Viscarra Rossel et al., 2014b) at depths of 0-5

216   cm, 5-15 cm and 15-30 cm which are useful for applying to rover surveys. The Soil and Landscape Grid of

217   Australia does not provide any lattice water information but it does provide information on clay content

218   (Viscarra Rossel et al., 2014c) and others (Greacen, 1981; Avery et al., 2016) have shown that clay content is

219   often a good predictor of lattice water. As an additional part ofIn this study we investigated whether such a

220 relationship existing for the soils in the study area. To do this we collected 36 samples for lattice water analysis;

221 this included 25 distributed samples in the broad scale survey area, 9 samples across the intensive scale survey

222 area and the 2 samples collected as part of the calibration of the static probes. These samples were from cores

223 extracted from 0-30 cm depth. The spatial maps of bulk density, clay content and organic carbon used in the

224 rover calculation procedures are shown in Figure 3, also shown for site characterisation is the digital elevation

225 model for the survey area.

227 Use of Eq. 5 in rover surveys also requires specification of a suitable N_0 value. For the static sensors this value is

228 derived through the calibration procedures. To calculate N_0 for the rover we undertook side-by-side comparisons

229 with the static sensors which involved parking next to a static sensor for 12 hours prior to a survey. The average

230 counts from the rover and static sensor were then compared to derive a suitable scaling approach to derive a

231 rover-specific N_0. Similar cosmic-ray neutron sensor cross-calibrations were undertaken by (Baatz et al., 2015)

232 to account for sensor specific differences. Both broad scale and intensive scale surveys were undertaken on three

233 separate occasions on consecutive days during April 2016, June 2016 and March 2017.

235 Interpolation of the rover count data was required to produce a spatial representation of count rates for the entire

236 survey area. To achieve this the Variogram Estimation and Spatial Prediction with Error (VESPER) software

237 package (Minasny et al., 2005) was used. VESPER was used to undertake conventional kriging with a global

238 variogram. An exponential variogram model was used for both survey scales and an interpolated grid of

239 corrected rover count rate was produced at 90 m resolution to match that of the underlying soils information.

241 **2.4   Comparison data sets**

242 Two independent datasets were utilised for comparison to soil moisture estimates from our rover surveys; 1)

243 opportunistic point samples collected during each survey, and 2) modelled soil moisture estimates from the

244 Australian Bureau of Meteorology's Australian Water Resources Assessment Landscape model, known as

245 AWRA-L.

247 Soil samples were collected at approximate predefined points, as shown in Figure 2, during each of the rover

248 surveys. A full set of samples was collected during the April 16 surveys and smaller sub-sets were collected

249 during the later surveys. At each sampling location a single 0 - 30 cm core was extracted. Gravimetric water

250 content for these cores was determined by drying samples at 105°C for 24 hours. For comparison purposes,

251 rover volumetric soil moisture estimates for the nearest pixel (9 km resolution for broad scale and 1 km

252 resolution for intensive) were extracted and divided by the corresponding average bulk density for that pixel to

253 produce an equivalent gravimetric estimate of soil moisture. We note here that there is a large scale discrepancy

254 between these datasets and highlight that the point samples only offer an approximate guide as to the accuracy

255 of rover survey results.

257 AWRA-L is a daily 0.05° (~5km) grid based, distributed water balance model. It simulates the flow of water

258 through the landscape with rainfall entering the grid cell through the vegetation and soil moisture stores and

259 leaving the grid cell through evapotranspiration, runoff or deep drainage to the groundwater. The

260 implementation and testing of the AWRA-L model has been described by numerous authors (Wallace et al.,

261 2013; Van Dijk, 2010; Viney et al., 2014). Of particular interest to this study is the AWRA-L estimate of root

262 zone soil moisture which covers a depth of 0 - 100 cm. The root zone represents a deeper soil zone than the

263 effective depth of the rover but provides our best source of comparison data. When comparing 5 km resolution

264 AWRA-L soil moisture estimates to those from the 9 km resolution broad scale rover survey the nearest

265 AWRA-L pixel to the 9km pixel centroid was used. When comparing the AWRA-L soil moisture to the 1 km

266 resolution intensive scale survey the intensive scale pixels were grouped to produce a corresponding 5 km

267 resolution product. AWRA-L soil moisture was reported in percentage capacity between 0 - 100% while the

268 rover results were in volumetric units, no attempt was made to convert between units and the comparison

269 focused on the strength of the fit between the data sets.

270 ## 3   Results

271 ### 3.1   Static CRNS calibration

272 ~~Prior to deployment, the two static sensors were run side-by-side for a period of 4 days to determine if there~~

273 ~~were any differences in counting rates that were not attributable to local conditions. Over this period the average~~

274 ~~counting rate differed by less than 1%, thus giving confidence that differences between sensors reflect local site~~

275 ~~characteristics alone.~~ Calibration of the two CRNS occurred under different soil moisture conditions; at Bennetts

276 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

277 calibration curve to these two sites (Figure 4) resulted in ~~remarkable~~ very similar~~similarity in derived~~ dry soil

278 (N_0) counting rates with analysis of the data collected at Bennetts producing an N_0 of 1541 c h^{-1} and that from

279 Bishes producing an N_0 of 1583 c h^{-1}. Across the soil moisture range of 0 to 0.5 m^3 m^{-3} the average soil moisture

280 difference between the two curves in Figure 4 was 0.019 m^3 m^{-3}. These differences are very small and reflect the

281 fact that hydrogen represented by the biomass pool is basically non-existent at these sites.

282 ### 3.2   Rover calibration

283 Calibration of the rover was undertaken through side-by-side comparison with the Bennetts CRNS and the

284 Bishes CRNS on two separate occasions each. These comparisons covered a range of soil moisture conditions

285 over four separate 12 h periods. Table 1 shows the corresponding neutron count rate for the rover and each

286 CRNS and the scaling factor that converts static CRNS counting rate to a rover equivalent; this scaling factor is

287 used to scale the N_0 values derived for each static sensor to an equivalent N_0 for the rover. Despite the

288 differences in conditions and site characteristics, the scaling factor remained relatively constant, as did the

289 derived N_0 for each comparison period. Given the relatively constant relationship between the rover and static

290 sensors an average N_0 of 460 c min^{-1} was derived and this value was applied across all surveys.

291 ### 3.3   Spatial lattice water information

292 ~~The volumetric soil moisture equation for cosmic-ray soil moisture measurements (Eq. 5) requires information~~

293 ~~on soil organic matter content, bulk density and lattice water. For our rover surveys spatial data sets exist for~~

294 ~~organic matter and bulk density but not for lattice water. A relationship between clay content and lattice water~~

295 ~~content has been noted by others therefore samples were collected to test for similar relationships across our~~

296 ~~survey area.~~ A comparison of clay content and lattice water content for 36 spatially distributed samples shows a

297 strong linear relationship (R^2 =0.7) across a broad range of clay content (4–56%) (Figure 5). This relationship

298 was applied to the spatial clay content data set from the Soil and Landscape Grid of Australia (Viscarra Rossel

299 et al., 2014c) to produce an equivalent lattice water dataset at 90 m resolution which was utilised in rover

300 surveys.

3.4 Spatial estimation

302 Example variograms from the kriging procedures used for broad scale and intensive surveys are shown in Figure

303 6. Both surveys utilise exponential variogram models however the fit is different with the intensive scale

304 surveys having a distinct 'sill' and broad scale variograms showing no 'sill' at all. The 'sill' in a variogram

305 represents the value at which the fitted model levels out (see Figure 6). The presence of a sill indicates that there

306 is a distance (known as the 'range') between pairs of points beyond which there is no spatial correlation. The

307 range is important as it is related to the spatial scale of the variability in neutron intensity. The lack of a sill for

308 the broad scale survey reflects differences in variability in neutron observations at this larger scale. The

309 variogram model for the intensive surveys showed more cyclicity (or 'hole effect') which could be related to

310 underlying geological periodicity (Yang and Kaleita, 2007). The empirical variograms were well described by

311 the exponential models giving confidence in interpolated rover counts across the respective survey areas.

3.5 Intensive scale rover surveys

313 Interpolated counts and derived volumetric soil moisture content for each of the three intensive scale surveys is

314 shown in Figure 7. A large range in soil moisture content was observed over the three surveys with values

315 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

316 rates and, hence, lower soil moisture were consistently observed in the central northern region of the survey

317 area. This area is characterised by a ridge of sandy soil with rock fragments and is known locally as 'Sandhill'.

318 Wetter soil moisture conditions were observed through the central and southern parts of the survey area. ~~We~~

319 ~~note here that although the data are presented at 90 m resolution this is due to calculations being undertaken at~~

320 ~~the scale of the underlying soil grid; the intended output of this survey is a 1 x 1 km soil moisture product.~~

321

322 Comparison of intensive rover survey soil moisture estimates for the CRNS locations at the three different

323 survey dates shows excellent agreement between the two measurement methods (Figure 8). The rover survey

324 estimate is taken from the 1 km resolution soil moisture estimate for the corresponding CRNS pixel.

325 Comparisons of estimates for the Bennetts CRNS shows differences of less than 0.025 m^3 m^{-3} for all three

326 occasions. The rover survey estimates tended to underestimate the soil moisture measured at the Bishes CRNS.

327 The largest difference was during the April 2016 survey where soil moisture was underestimated by 0.04 m^3 m^{-}

328 ^{3}. It is possible that this underestimation is a result of local interpolation issues. The Bishes CRNS is in close

329 proximity to the sandy ridge known as 'Sandhill' which represents a distinct zone of low soil moisture (Figure

330 7). The effect of this abrupt change is likely to be 'smoothed' within the area that also encompasses the Bishes

331 CRNS.

9

Figure 9a shows a comparison of rover gravimetric soil moisture against corresponding soil moisture from the grab samples collected during each survey. The comparison shows strong correlation (R^2 = 0.80) and data points are scattered around the 1:1 line. There is more scatter observed in the data under wetter conditions but this is likely to be related to a greater relative difference in spatial soil moisture following rainfall events. Similarly, the comparison of rover volumetric soil moisture against modelled root zone soil moisture from the AWRA-L model (Figure 9b) also shows good correlation (R^2 = 0.79). This comparison is complicated by the fact that the rover estimate represents an effective measurement depth of between 10 to 25 cm while the root zone soil moisture is an estimate between 0 and 100 cm, despite this the agreement is still good. Comparison to these two independent soil moisture products with the rover surveys increases confidence in rover survey results at the intensive scale.

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 10 and the intensive scale rover survey from March 2017 has been used to derive property average soil moisture conditions in this figure. The average size of the identified properties is approximately 1 km².

Point-to-area linear regression modelling based on continuous CRNS measurements from the Bennetts sensor and three intensive rover surveys was applied to 50 properties identified in the intensive survey area and 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 were derived with an average R^2 value of 0.97 (range = 0.87-1.00, see Table A1 for full results). We note here that only three surveys were available for developing these relationship and further surveys and cross validation is recommended for future work. Application of these regression models to derive time-series of property scale soil moisture for three example properties is given in Figure 11Figure 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 12Figure 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-

371   east. The driest soil moisture conditions were experienced during the April 2016 survey with a mean soil

372   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

373   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

374   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}).

375

376   Figure 13a shows a comparison of rover gravimetric soil moisture against corresponding soil moisture from the

377   grab samples collected during each survey. The comparison shows reasonable correlation (R^2 = 0.64) and data

378   points tend to be scattered around the 1:1 line. Given the scale difference between these products (9 km vs point

379   sample) the observed scatter is not surprising. Figure 13b shows a comparison of rover volumetric soil moisture

380   against modelled root zone soil moisture from the AWRA-L model. The closer scale match between these two

381   products (9 km vs 5 km) when compared to the point samples, results in a much higher correlation between the

382   two data sets (R^2 = 0.78). As with the intensive survey comparison interpretation of the results is complicated

383   because the measurement depth of the rover (10 to 25 cm) is much less than the AWRA-L root zone soil

384   moisture (0 and 100 cm). Despite these differences the two products are still remarkably well correlated and the

385   good agreement between the rover estimates and the AWRA-L estimates, both spatially and across a range of

386   soil moisture conditions, provides further evidence that the rover experimental design and data processing

387   procedures are reliable.

388

389   ~~The nested design of the intensive and broad scale surveys (Figure 2) enables the accuracy of broad scale survey~~

390   ~~estimates to be assessed. To undertake such an analysis, we selected a~~ Broad scale survey soil moisture

391   estimates were also tested by comparison with intensive survey results at scales of 1, 3 and 9 km in an

392   overlapping 9 x 9 km region ~~within the area of survey overlap (~~(Figure 2). ~~) and derived corresponding soil~~

393   ~~moisture estimates at resolutions of 1, 3 and 9 km. The intensive survey results can be considered as a point of~~

394   ~~truth for broad survey results.~~ The difference in soil moisture estimates between the broad and intensive scale

395   surveys for different resolutions on each of the three survey dates is shown in Figure 14~~Figure 12~~. The broad

396   scale survey estimates are clearly not a good representation of 1 x 1 km scale soil moisture as survey speeds and

397   sampling points are not detailed enough to pick up local soil moisture variations at current counting rates.

398   Differences of up to ±0.10 m^3 m^{-3} were observed. At 3 x 3 km resolution the performance of the broad scale

399   survey estimates improves but there are still some distinct zones where soil moisture differed by as much as

400   ±0.06 m^3 m^{-3}. At the 9 x 9 km scale, for which the broad scale surveys were designed, differences in soil

401   moisture between the intensive and broad scale surveys was minimal. On all three occasions the difference was

402   less than 0.005 m^3 m^{-3}. These comparisons validate our broad scale experimental design and give confidence in

403   the 9 x 9 km resolution soil moisture produced from our rover surveys.

404   **4   Discussion**

405   Static CRNS calibration at Bishes and Bennetts produced very similar dry soil counting rate (N_0). This similarity

406   has resulted because hydrogen in soil water, lattice water and organic matter is accounted for in the calibration

407   process and because both sites are devoid of above ground biomass. The effect of biomass on N_0 has been noted

408   by Hawdon et al. (2014) who compared N_0 values from eight probes from across the Australian CRNS network

409   with site biomass and also by Baatz et al. (2015) who proposed an empirical biomass correction for CRNS

410   calibration. This finding has important implications for rover surveys in this region as the landscape in the

411   Mallee region is almost entirely cleared of forest and above ground biomass is represented by pasture and crop

412   cover. McJannet et al. (2014) calculated that pasture represented a biomass water equivalent of just 0.6 mm a

413   value similar to that derived by Baatz et al. (2015) for areas dominated by crops; these small values show that

414   these small hydrogen pools will to have little impact on neutron counts (McJannet et al., 2014).

415

416   In this present study the N_0 value for converting rover neutron counting rates to soil moisture content was

417   derived through side by side comparison with the two CRNS sensors. A similar approach was employed by

418   Chrisman and Zreda (2013) using a single CRNS as a reference point and by Dong et al. (2014) using a network

419   of in situ measurements. Rover surveys undertaken by Franz et al. (2015) also used comparison with static

420   CRNS sensors but in their investigations a further correction was introduced to account for variations in above

421   ground biomass. Locations with greater biomass should adopt a calibration schemes that include this hydrogen

422   pool (i.e. Baatz et al., 2015; Franz et al., 2013).

423

424   Rover surveys require information on the spatial variation in bulk density, soil organic matter and lattice water

425   for calculation of soil moisture content using conventional approaches. While pre-existing bulk density and

426   organic matter datasets exist for Australia we had to derive a lattice water dataset based on a strong region-wide

427   relationship with clay content. The relationship we derived for the study area was different to that proposed by

428   Greacen (1981) for Australian soils and may reflect differences in the soil types included in the analysis. With

429   the intent of producing a similar spatial lattice water dataset for the continental United States, Avery et al.

430   (2016) derived relationships with clay content but found that relationships were weak for many soil taxonomic

431   group. For best local results a spatial sampling such as that utilised in this present study is recommended.

432

433   A factor that has not been accounted for in our rover surveys is the potential impacts of roads on our survey

434   results. By design roads will have a low moisture content and the impact of this narrow strip within the sensor

435   footprint on survey results has not yet been accounted for in any operational rover studies reported in the

436   literature. Using neutron modelling approaches Köhli et al. (2015) demonstrated that a CRNS is most sensitive

437   to soil moisture in the nearest tens of metres and showed that dry roads can contribute to an over estimate of

438   neutron counts by a few percent. The dry roads will be over-represented in the measured neutron intensity as the

439   sensitivity of neutron intensity to hydrogen is greater at the dry end of the scale (Andreasen et al., 2017a). A

440   more recent study by Schrön et al. (In Review) using neutron transport simulations and dedicated field

441   experiments supports the findings of Köhli et al. (2015). Schrön et al. (In Review) found that the effects of roads

442   are greatest when surrounding soil moisture is much higher than road moisture content. In the survey areas in

443   which our broad scale rover surveys were undertaken more than 70% of the roads were unsealed and many of

444   the sealed roads were only one lane wide; while this does not remove the issue it does lessen the potential

445   impact on reported results considerably. The impact of roads on our intensive scale surveys is likely to be even

446   less as 60% of the observations were made while driving around property boundaries (i.e. not properly formed

447   roads) and a further 30% were on unsealed roads. While the impact of roads may not be a major issue for the

448   present study it is an issue that needs some warrants consideration in future surveys.

449

450   Intensive scale surveys were designed to produce a 1 x 1 km resolution soil moisture product and comparison to

451 static CRNS observations, spatially distributed point samples and AWRA-L model predictions supports this.

452 While the point samples and model estimates cannot be considered the 'truth' they do provide a good guide as to

453 rover performance and the agreement with these estimates provides confidence in intensive scale rover results.

454 Detailed soil moisture maps highlight the impact that soil properties have on observed soil moisture with sandier

455 locations being typically drier when compared to those with more clay. Property scale soil moisture estimates

456 led to the development of point-to-area style regression models which then enabled continuous estimates of soil

457 moisture to be made at the property scale. Property-scale regression models were strong but it is noted that these

458 are based on data from three surveys. A more thorough investigation is recommended and this should include

459 further surveys and cross validation experiments. We note thatT the opportunity also exists to use similar point-

460 to-area scaling techniques to derive high temporal resolution soil moisture products at other set resolutions (e.g.

461 1 km) which would make for ideal datasets for testing model and satellite soil moisture estimates. The

462 regression modelling undertaken showed that temporal patterns in soil moisture were strong. Similar

463 observations have been reported for other studies (Kachanoski and Jong, 1988; Grayson and Western, 1998;

464 Vachaud et al., 1985). According to Yang and Kaleita (2007) spatial patterns of soil moisture exhibit some

465 degree of temporal stability which is related to time invariant attributes such as topography and soil

466 characteristics. With the relatively flat topography in Mallee study area and the assumption that rainfall inputs

467 and crop growth are similar between properties, it is likely that differences in the slopes and intercepts of

468 relationship between CRNS observations and property scale soil moisture (see Table A1) are being controlled

469 by local soil characteristics. Changes in local crops and local scale differences in rainfall inputs (i.e. small

470 convective storms) do of course have the potential to change these point-to-area relationships but if these factors

471 can be accounted for then useful spatial and temporal soil moisture datasets can be produced.

472

473 Comparison of broad scale rover soil moisture estimates against those from point samples and the AWRA-L

474 model showed good agreement across both space and time, thus providing further evidence that the rover

475 experimental design and data processing procedures were reliable. Agreement between rover estimates and

476 model estimates was particularly good and this reflects the closer match in scale of these two products.

477 Comparison with emerging satellite, measurement, and modelled soil moisture products will help to further

478 assess rover approaches and results in the future. Broad scale surveys produced reliable soil moisture estimates

479 at 9 x 9 km resolution although the faster survey speeds and lower measurement density meant that this survey

480 was unable to distinguish many of the smaller scale soil moisture variations revealed at the finer resolution and

481 slower survey speeds of the intensive scale survey. This clearly supports the need to design rover surveys for the

482 scale of analysis to be eventually undertaken.

483 **5   Conclusion**

484   In this study we presented an investigation designed to produce soil moisture estimates across a range of scales.

485 Our investigation involved static CRNS sensors and rover surveys at both broad and intensive scales. We

486 established techniques for converting neutron counting rates from the rover to soil moisture using side-by-side

487 comparisons with static CRNS sensors and spatial datasets of soil characteristics. In particular we found that

488 lattice water was strongly related to clay content in the study area and used this relationship to derive a spatial

489 representation of lattice water.

490

491 Rover surveys were undertaken across soils ranging in moisture content from 0.01 to 0.30 m^3 m^{-3} and

492 comparison with spatial distributed point samples and model estimates showed that reliable results were

493 produced across all conditions. The slower driving speeds and denser sampling network of the intensive surveys

494 provided representation of local soil moisture variations at resolutions down to 1 x 1 km. Stability in observed

495 spatial patterns of soil moisture were used in a regression modelling approach to produce time series of property

496 scale soil moisture based on CRNS observations. Broad scale surveys, which incorporated higher driving speeds

497 and sparser sampling points, were shown to produce excellent representations of soil moisture at 9 x 9 km pixel

498 resolution making them well suited for assessing variation in this parameter at a regional scale. The multiscale

499 application of the rover makes it a unique tool for addressing soil moisture questions across scales previously

500 not possible. The multiscale soil moisture products produced in this study are well suited to future analysis of

501 both satellite soil moisture retrievals and finer scale soil moisture models.

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653 **6   Tables and captions**

654

655 **Table 1. Side-by-side comparison of average neutron counts for the static CRNS's (Bishes and Bennetts) and the**
656 **rover for 4 different 12 hour periods. Also shown are the <u>average soil moisture values for each date,</u> static CRP to**
657 **rover scaling factors and derived dry soil counting rate, N_0, for the rover. All counts are in c min-1 for application to**
658 **rover data.**

Date	Site	Static CRNS average counts (c min^{-1})	<u>Static CRNS average soil moisture (m^3 m^{-3})</u>	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	<u>0.08</u>	370.0	17.0	26.4	449
1 March 2017	Bishes	20.4	<u>0.10</u>	364.8	17.9	26.4	471
9 June 2016	Bennetts	15.23	<u>0.28</u>	268.1	17.6	25.7	452
2 March 2017	Bennetts	16.8	<u>0.16</u>	307.6	16.8	25.7	469
				Average	**17.3**	**Average**	**460**

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662 **7   Figures and captions**

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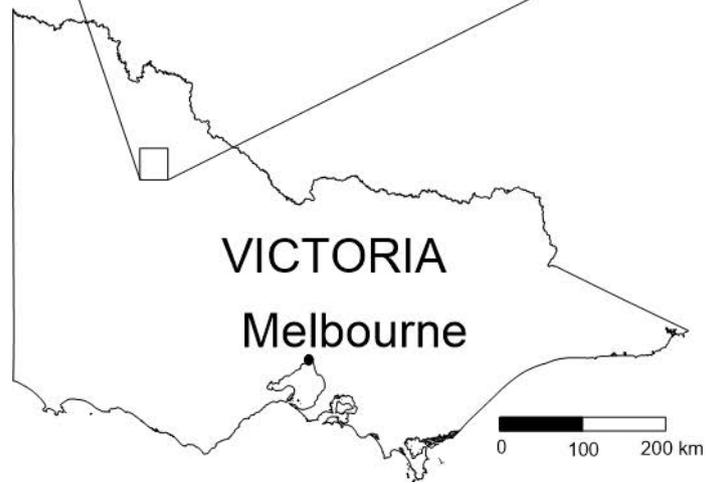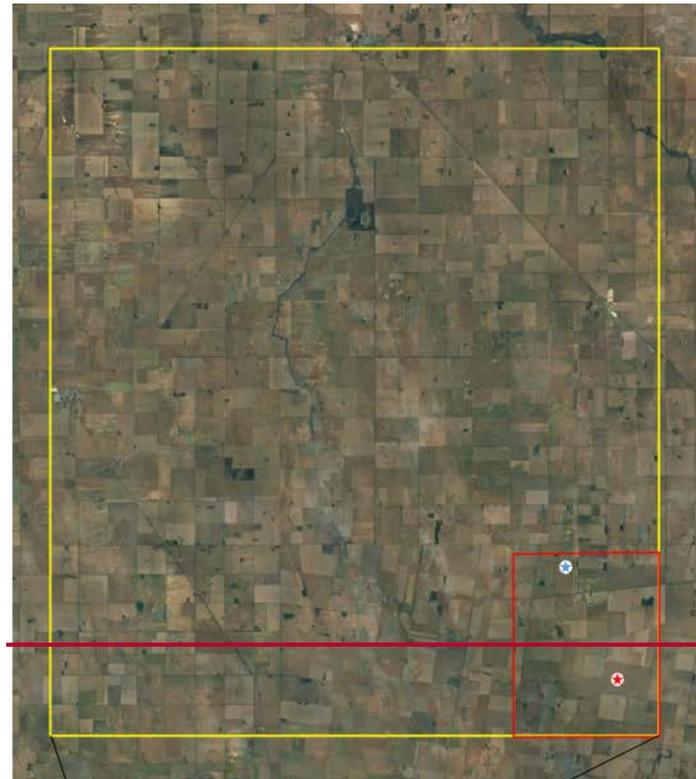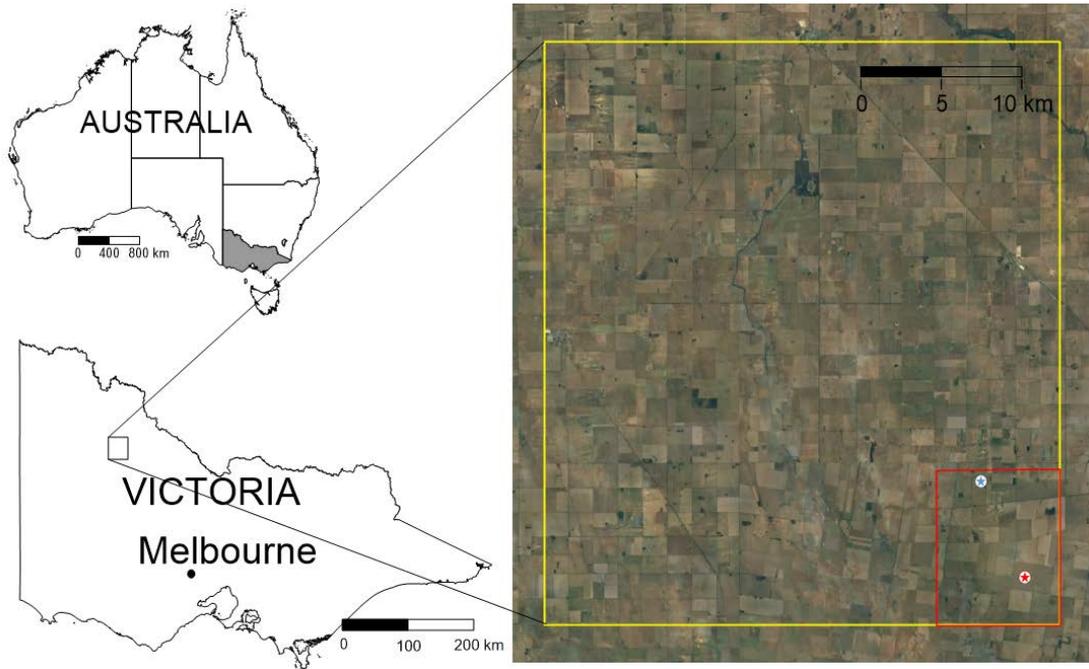
Figure 1. Location of field site in western Victoria, Australia. Yellow rectangle shows extent of broad scale rover surveys (36 x 36 km) and red rectangle shows extent of intensive surveys (10 x 10 km). Blue and red stars indicate the location of the Bishes and Bennetts cosmic-ray ~~soil moisture~~neutron sensors. Imagery data: Google, TerraMetrics 2017.

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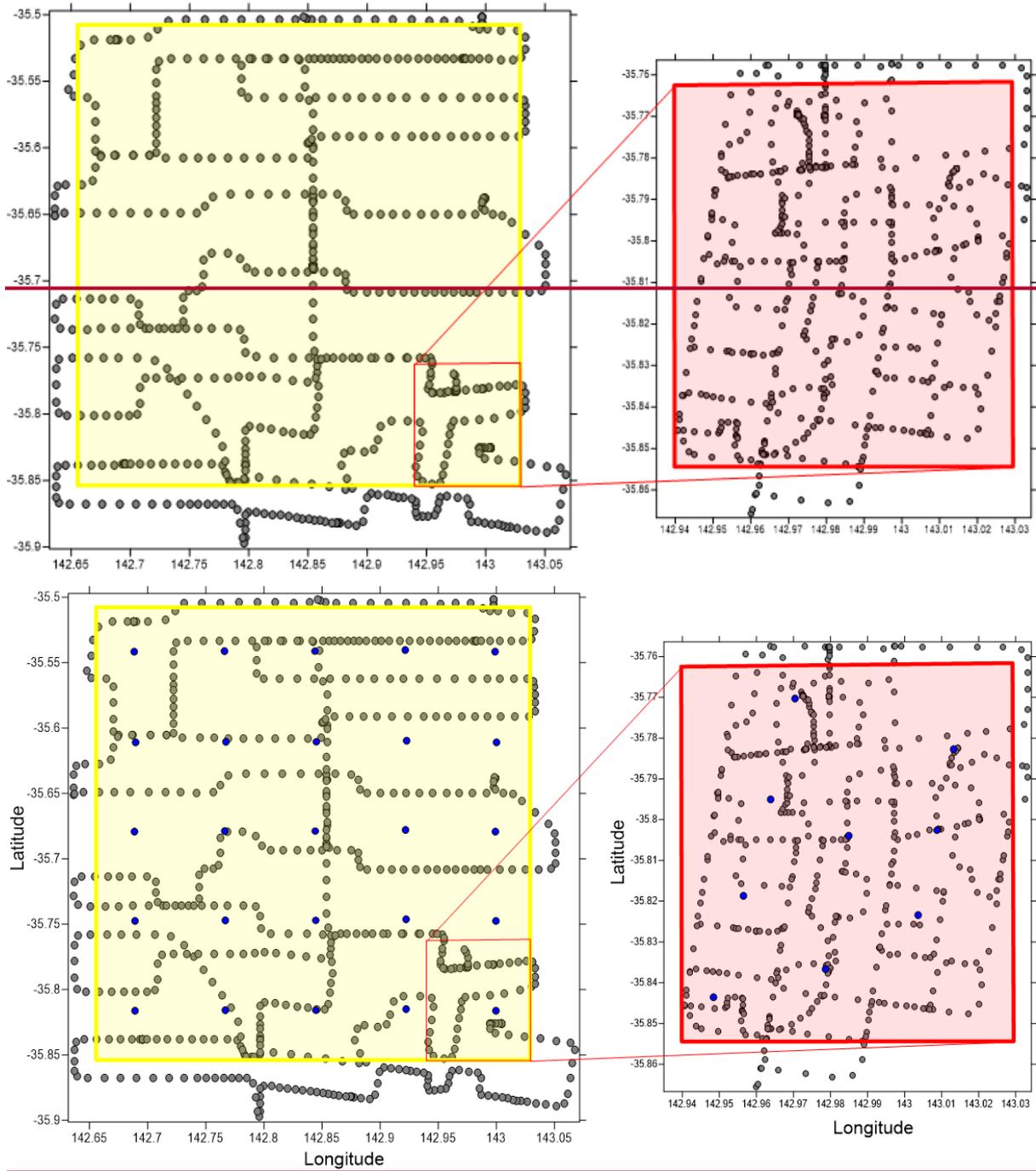
Figure 2. Rover survey extents and sampling points for the broad scale and intensive scale measurement campaigns.
Sampling points from April 2016. The yellow box (~36km x 36km) delineates the broad scale survey extent and the
red box (~10km x 10 km) delineates the intensive scale survey extent. Blue points in each figure represent
approximate locations of gravimetric soil moisture sampling points.

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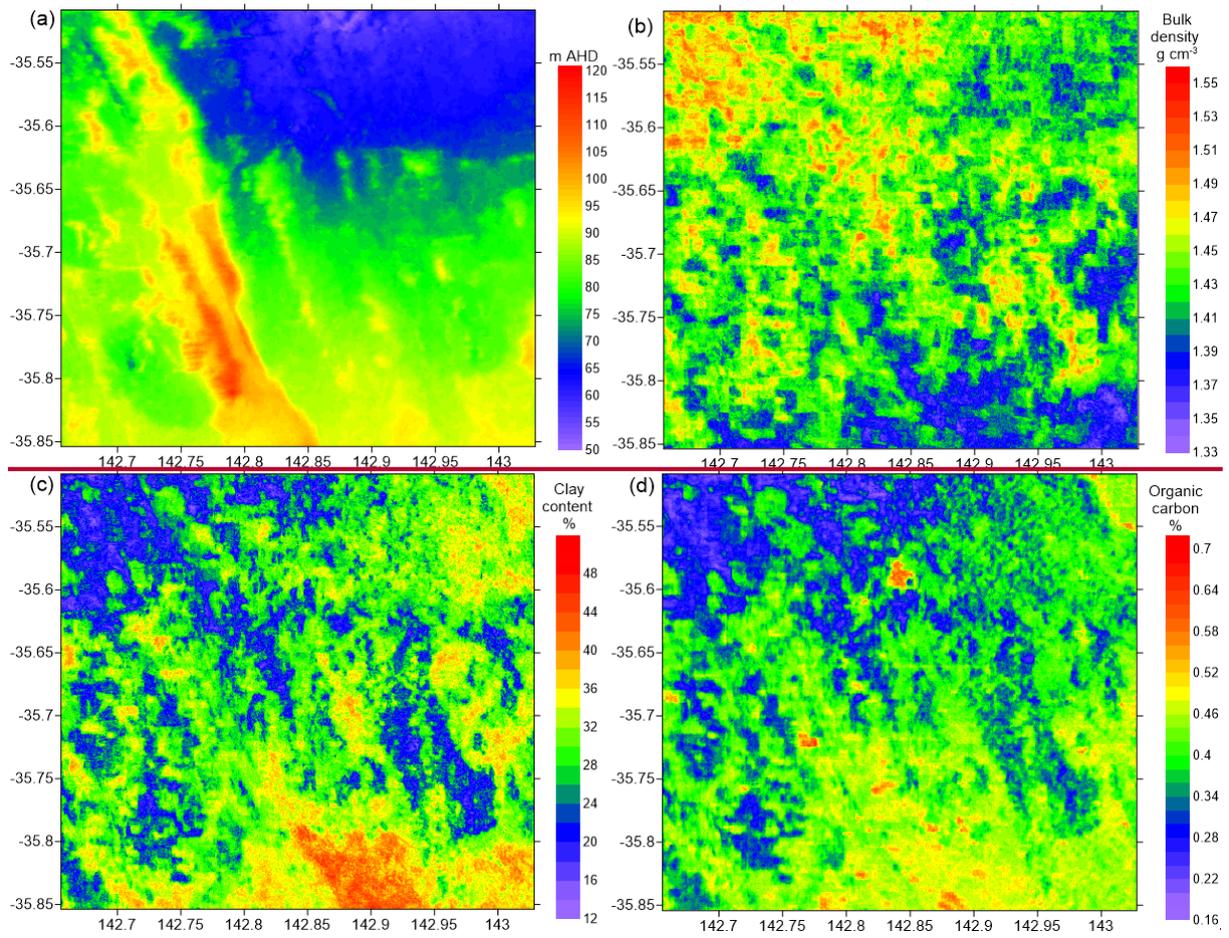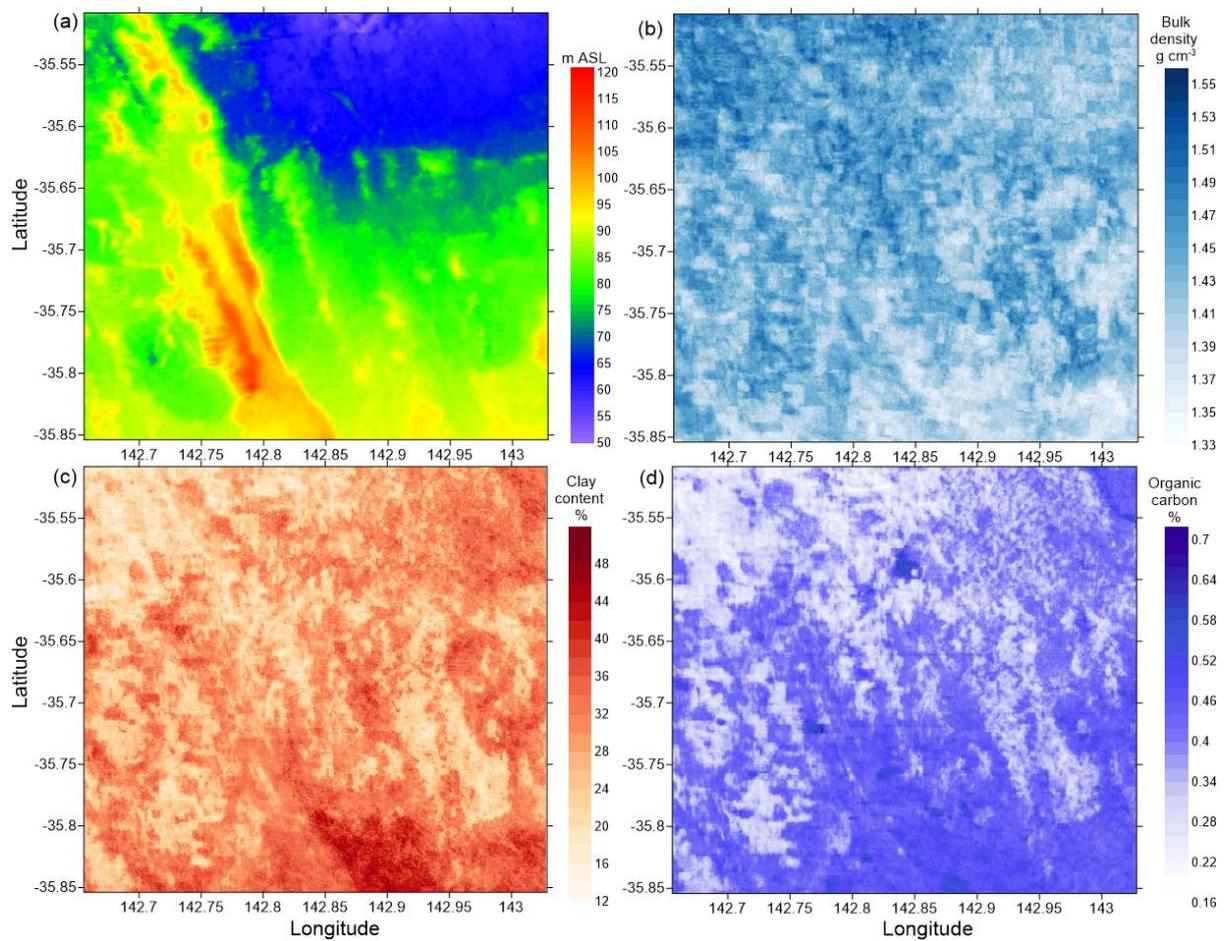
Figure 3. Field survey area DEM (a), depth weighted 0–30 cm bulk density (b), depth weighted 0–30 cm clay content (c), and depth weighted 0–30 cm organic matter content (d).

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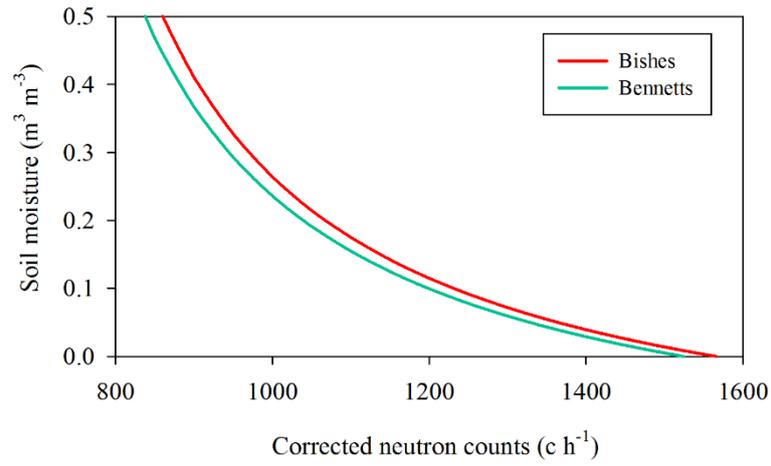
Figure 4. Calibration curves for converting corrected neutron counts to soil moisture content for the Bishes and Bennetts cosmic ray soil moisture sensors. The dry soil counting rate, N_0, is 1583 c h^{-1} for Bishes and 1541 c h^{-1} for Bennetts.

$$y = 0.00075x + 0.0121$$
$$R^2 = 0.7, p < 0.0001$$

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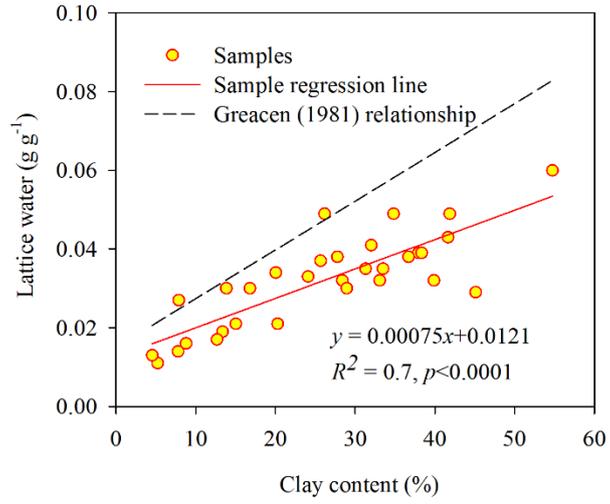
Figure 5. Clay content vs Lattice water showing sample points from the study area and fitted relationship. Also shown for reference is the relationship proposed by Greacen (1981).

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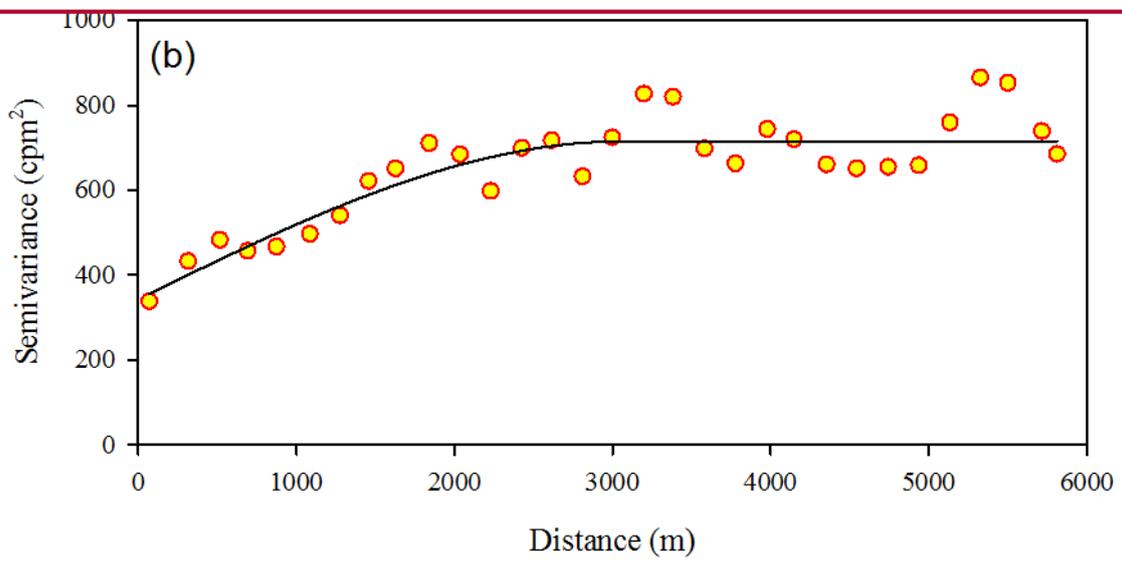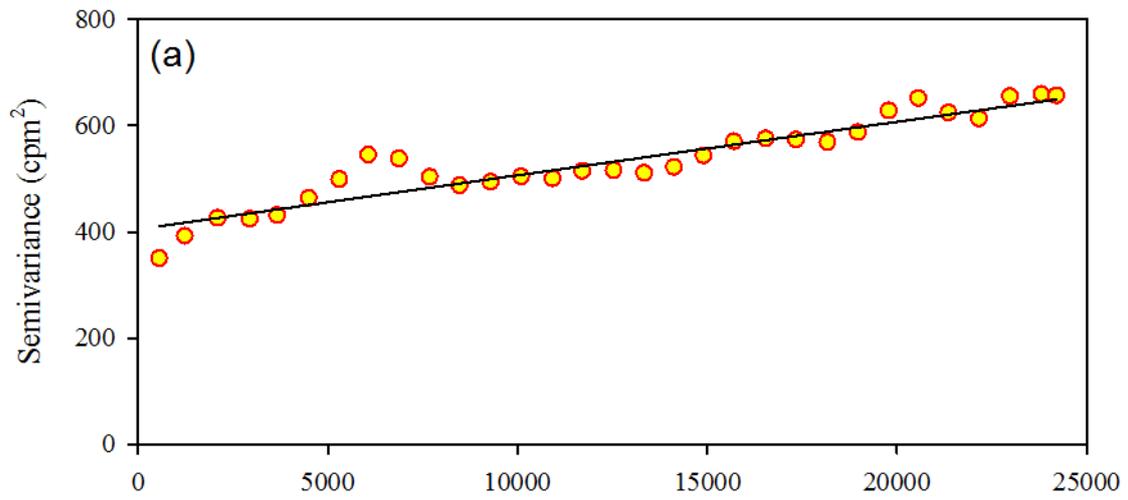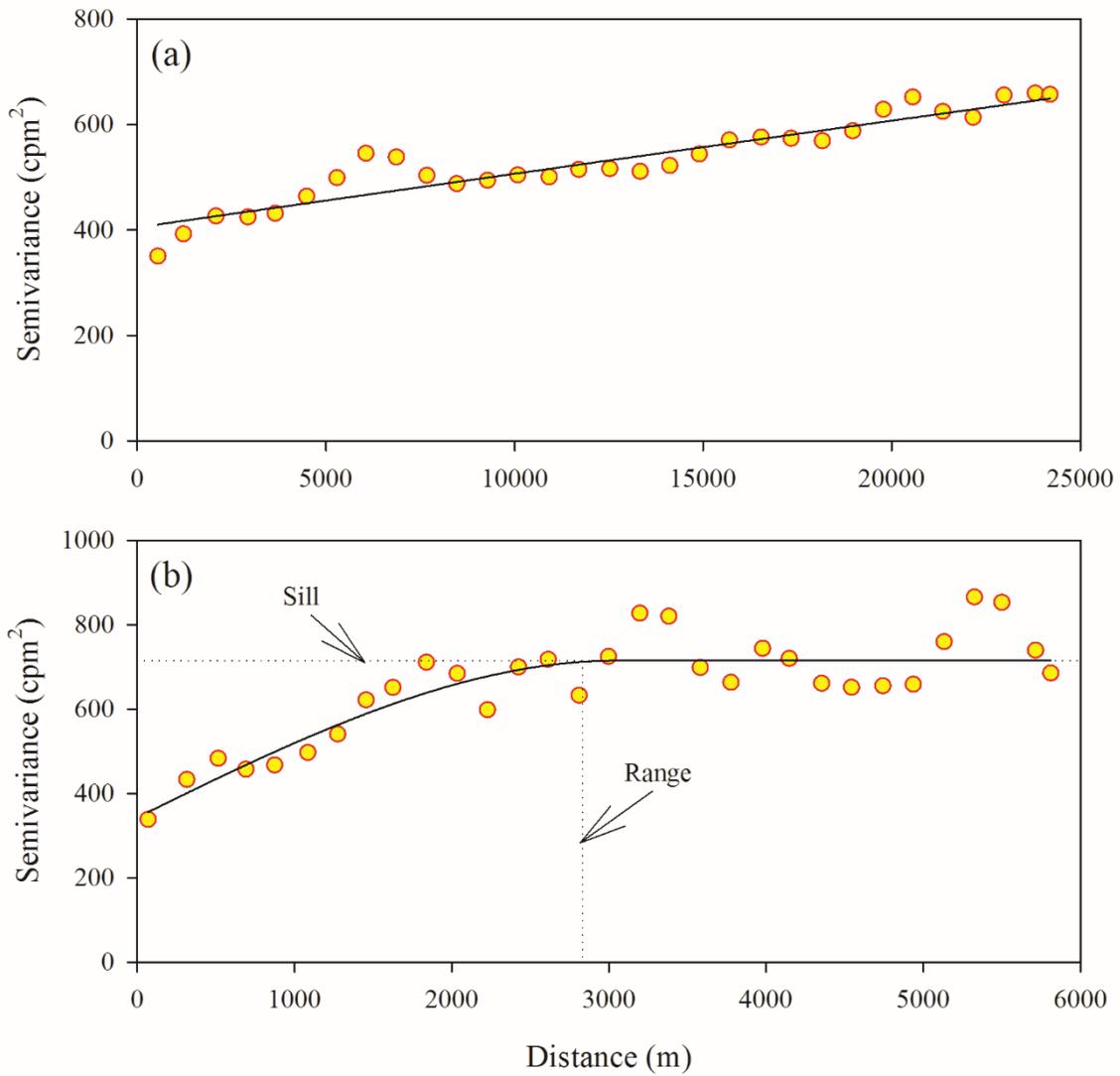
Figure 6. Example variograms used for block kriging for broad scale and intensive surveys. The broad scale variogram is from April 2016 (a) and the intensive scale variogram is from June 2016 (b). **The sill and the range are shown in (b).**
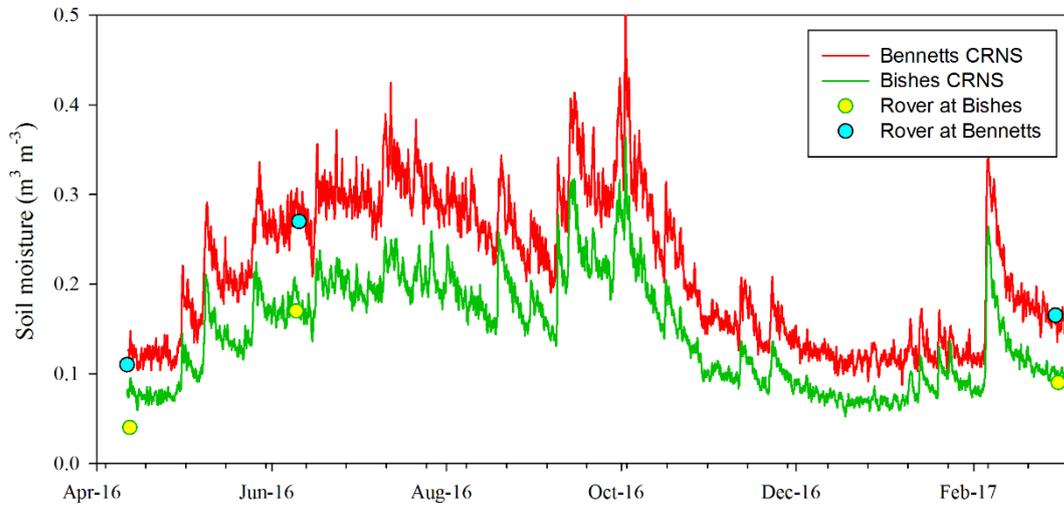
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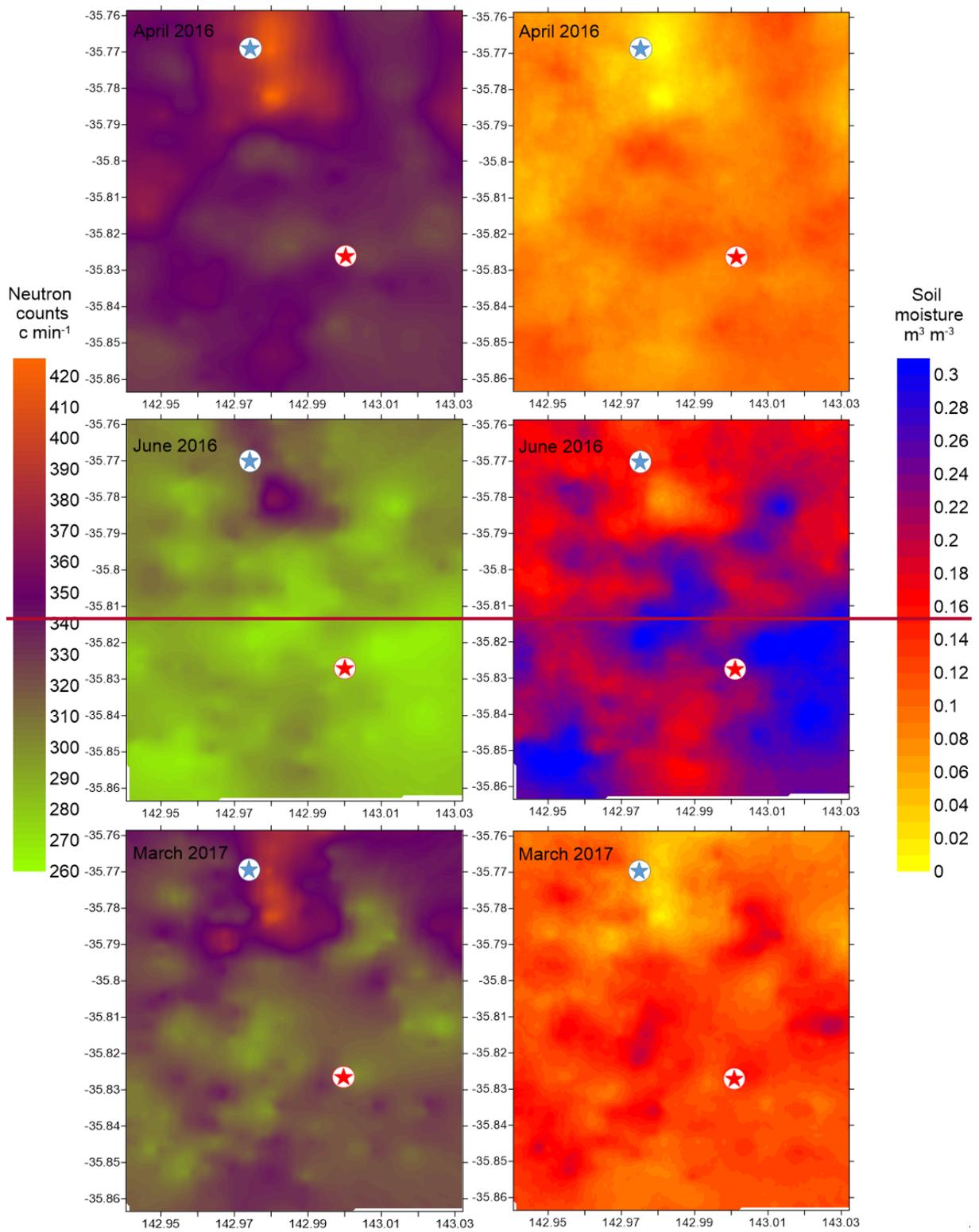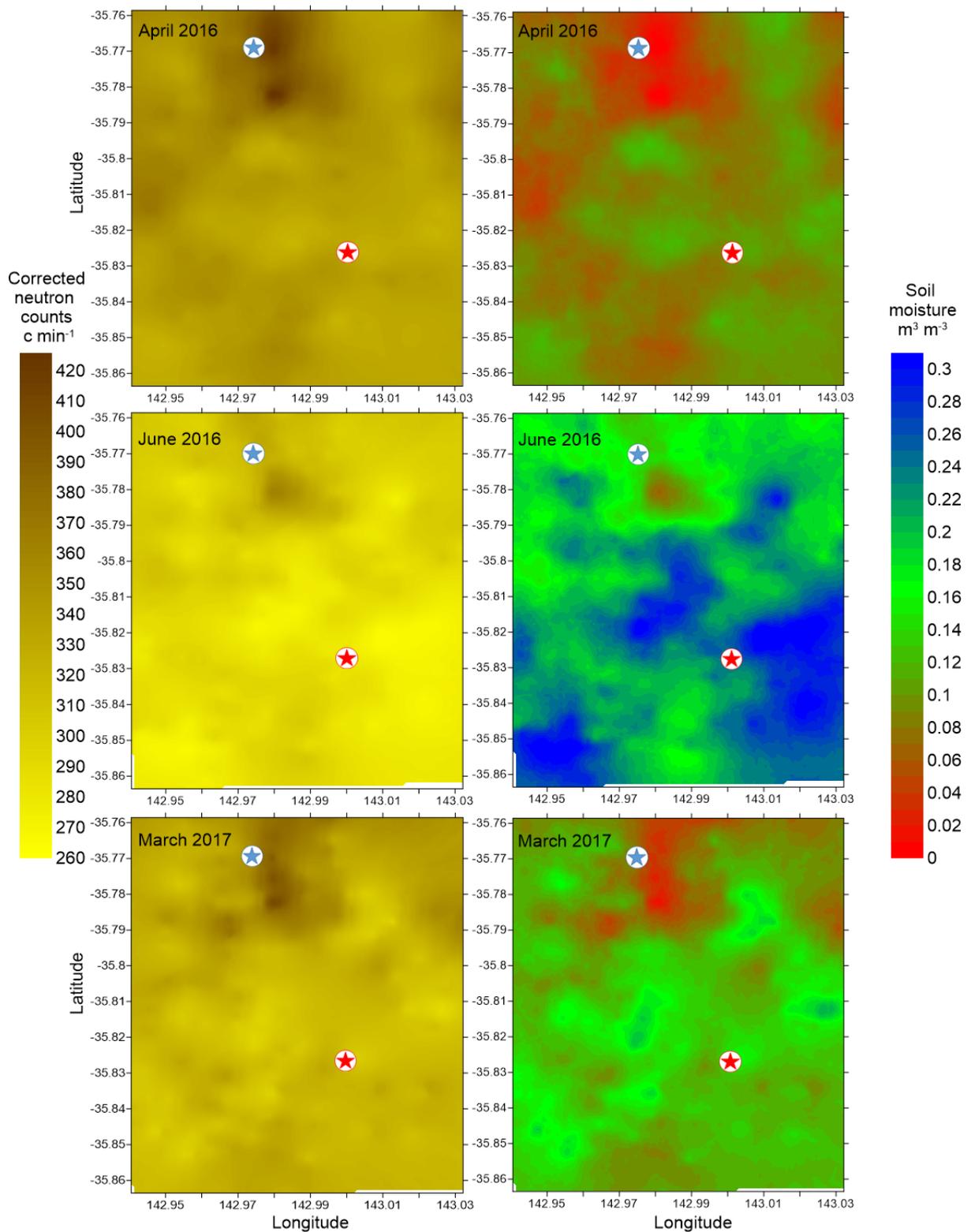
Figure 7. Interpolated <u>corrected neutron </u>counts (left column) and derived soil moisture (right column) for the three intensive scale surveys during April 2016, June 2016 and March 2017. Blue and red stars indicate the location of the Bishes and Bennetts cosmic-ray ~~soil moisture~~<u>neutron</u> sensors.
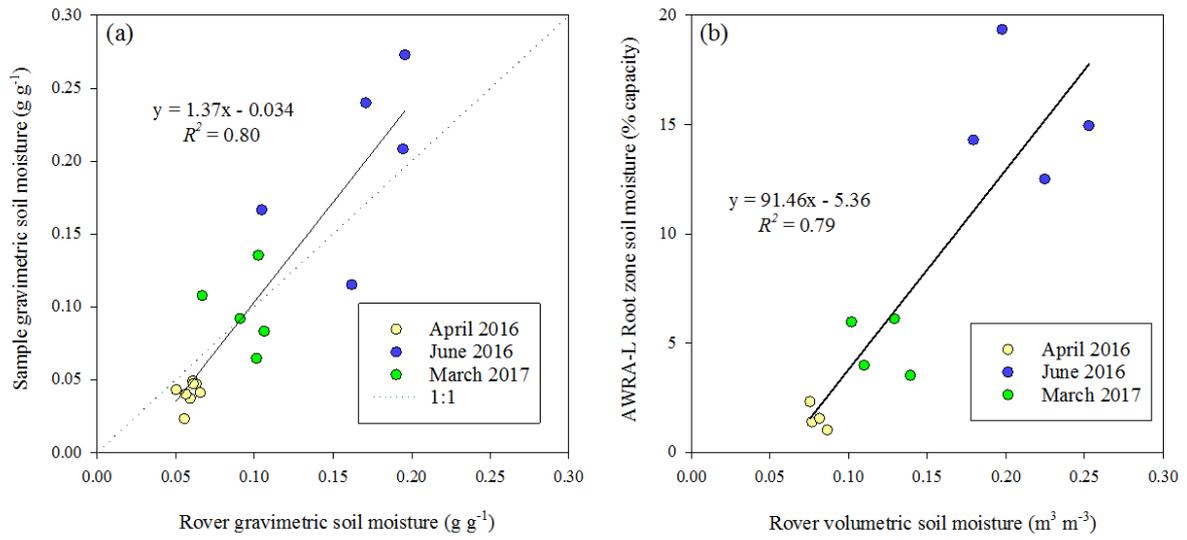
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712 **Figure 8. Comparison of Bennetts and Bishes CRNS soil moisture estimates and corresponding intensive rover survey**
713 **estimates for the CRNS locations for the three survey dates. Rover survey estimate is from 1 km resolution pixel**
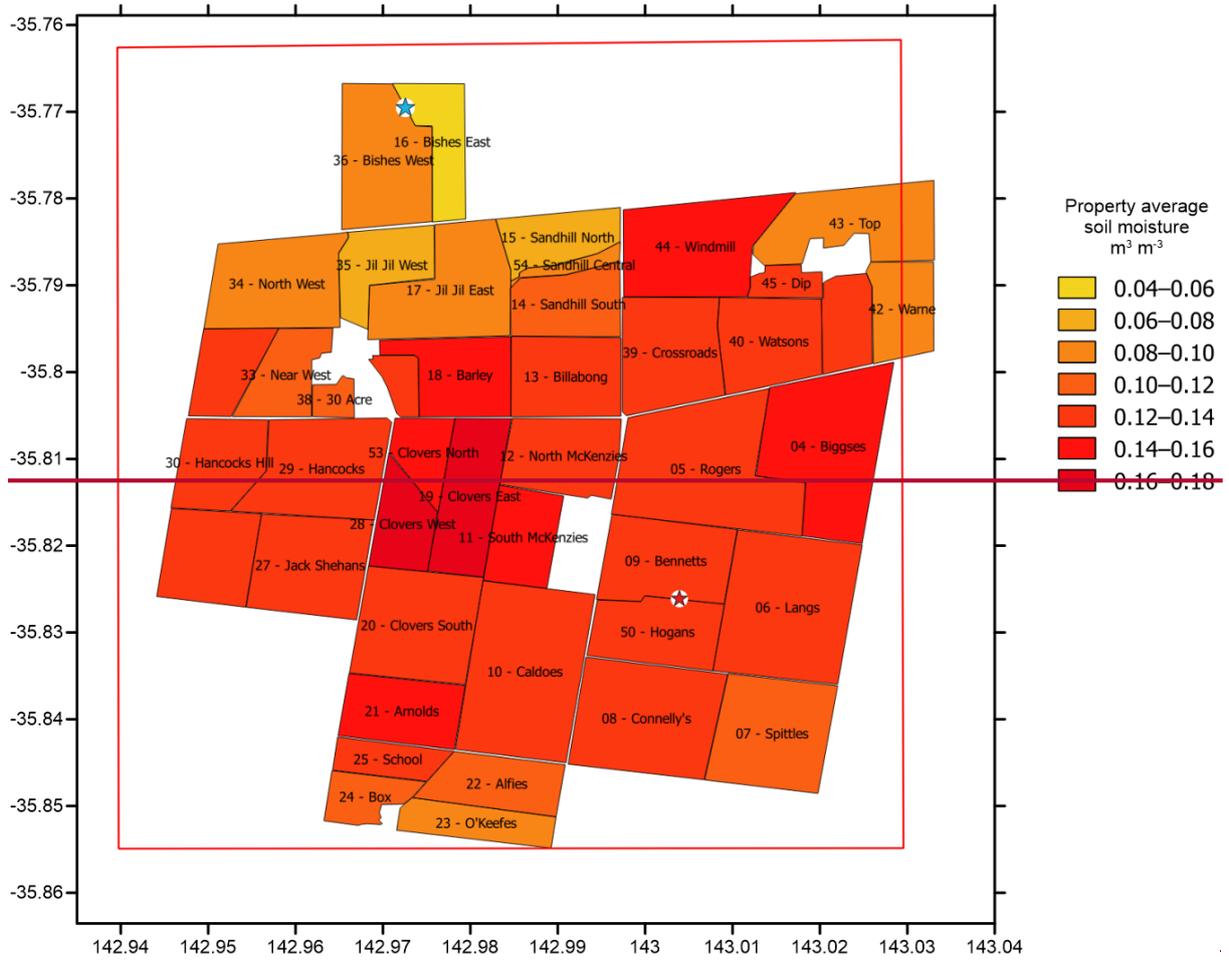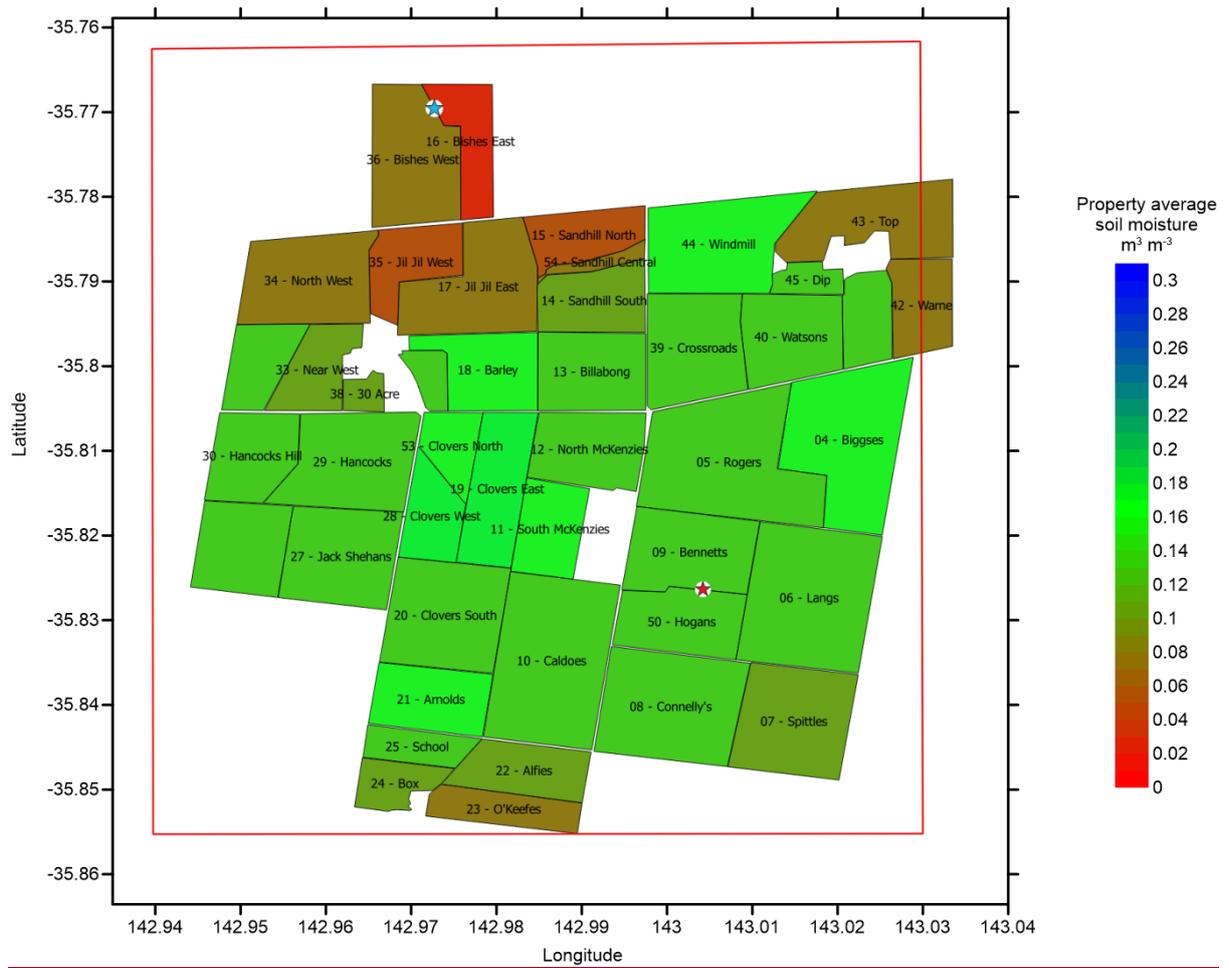714 **corresponding to each CRNS location.**

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Figure 9. Intensive rover survey gravimetric soil moisture (1 km resolution) versus point sample gravimetric soil moisture (a) and intensive rover survey soil moisture (up-scaled to 5 km resolution) versus AWRA-L root zone soil moisture (5 km resolution).
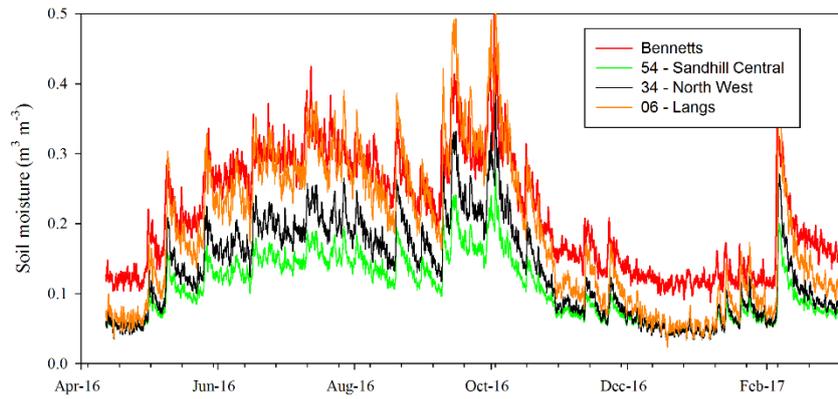
Property average
soil moisture
m³ m⁻³

- 0.04–0.06
- 0.06–0.08
- 0.08–0.10
- 0.10–0.12
- 0.12–0.14
- 0.14–0.16
- 0.16–0.18

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Figure 10. 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~~<u>neutron</u> sensors.
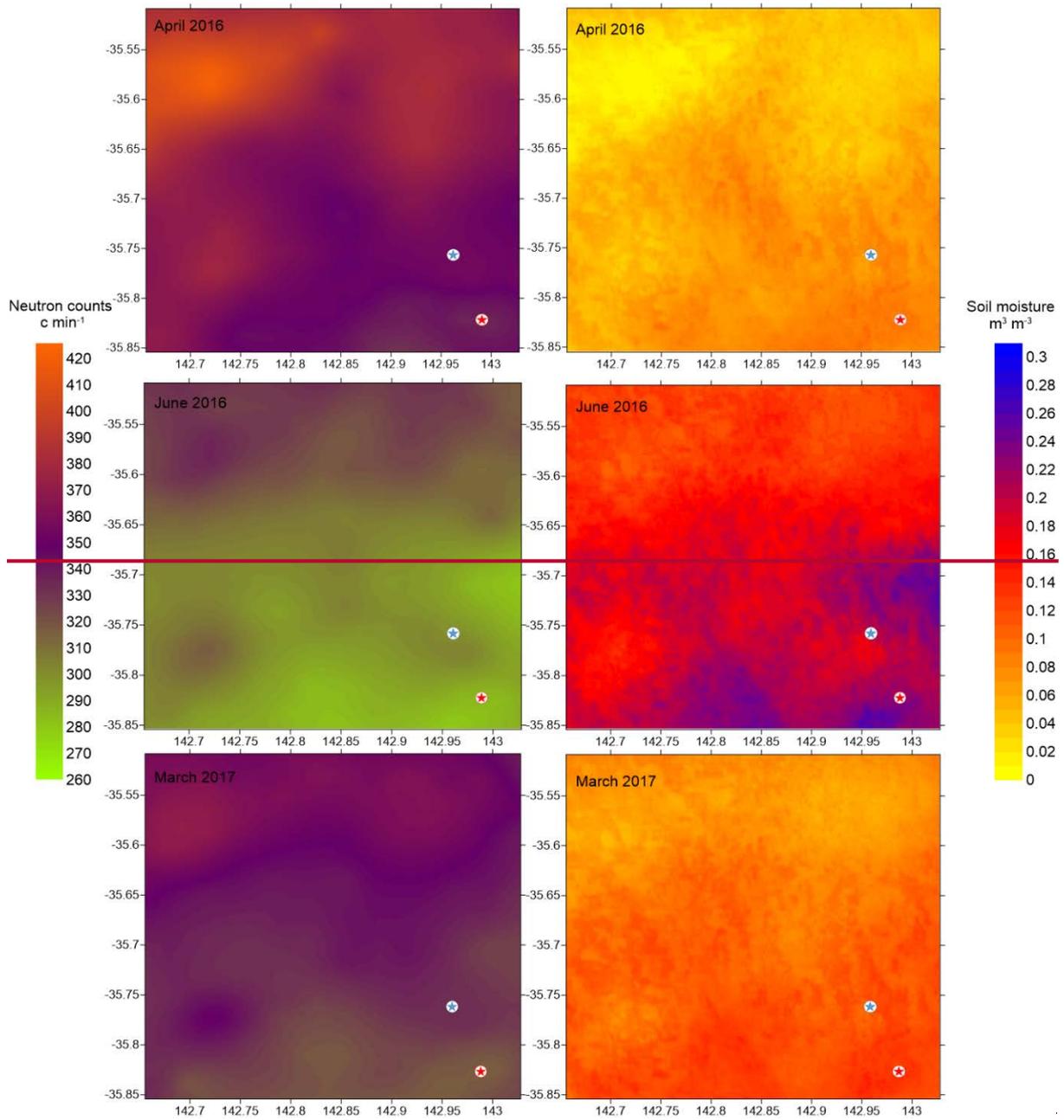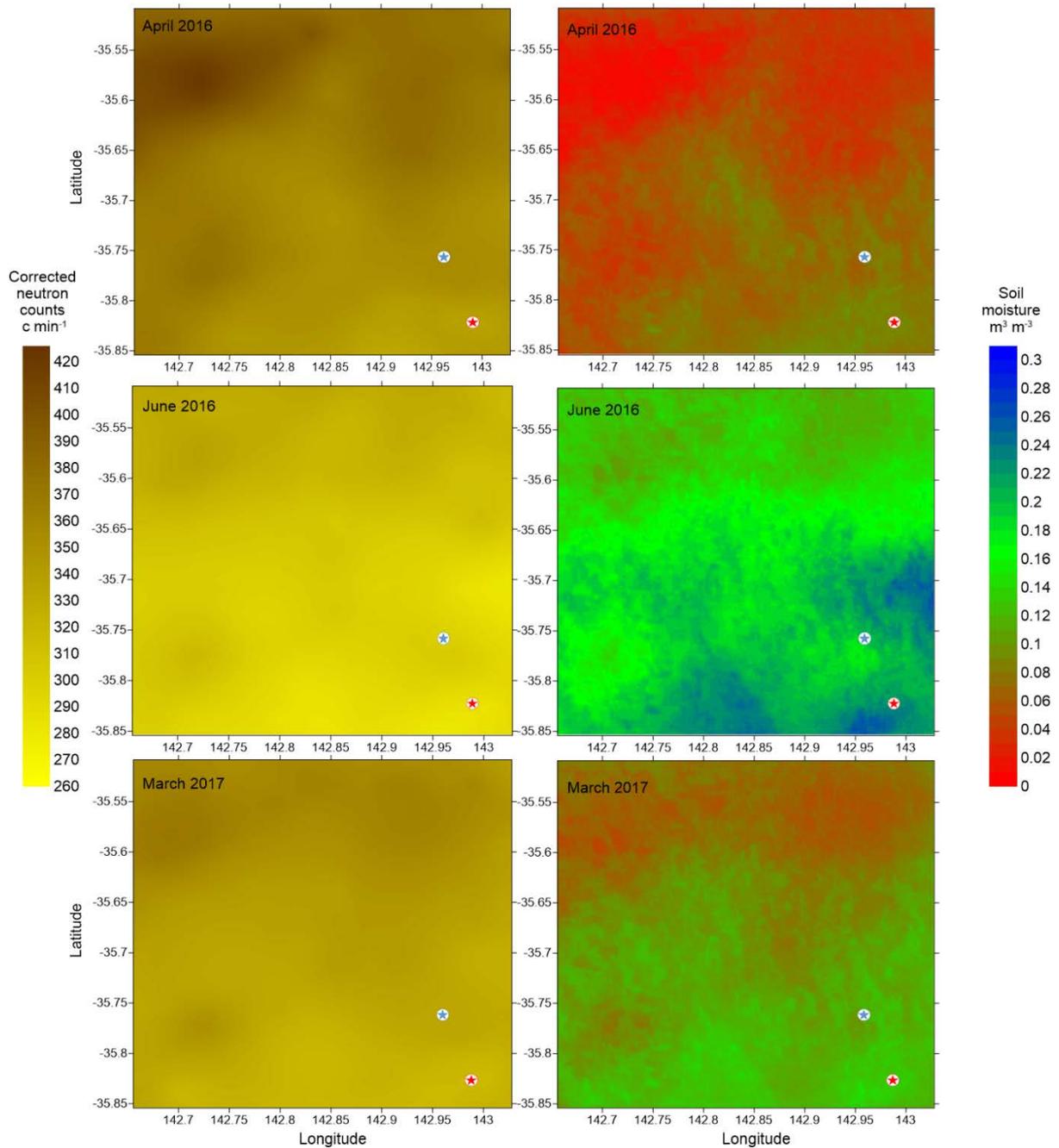
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Figure 11. Time series of average soil moisture for selected properties in the intensive scale survey area and corresponding soil moisture time series from the Bennetts cosmic-ray ~~soil moisture~~neutron sensor. Scaling relationships are provided in Table A1.
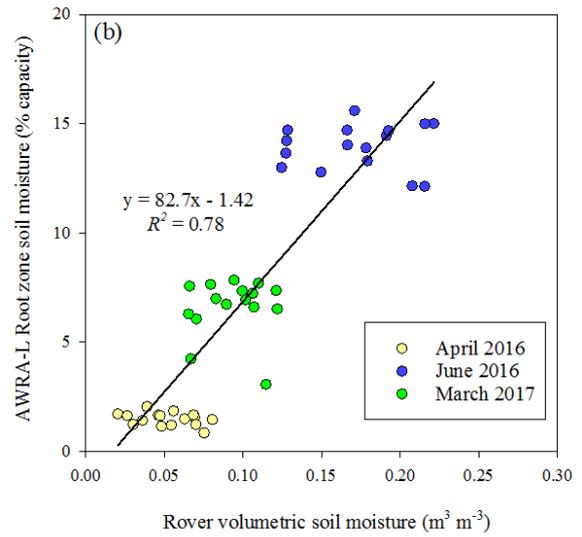
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Figure 12. Interpolated corrected neutron counts (left column) and derived soil moisture (right column) for the three broad scale surveys during April 2016, June 2016 and March 2017. Blue and red stars indicate the location of the Bishes and Bennetts cosmic-ray soil moistureneutron sensors.
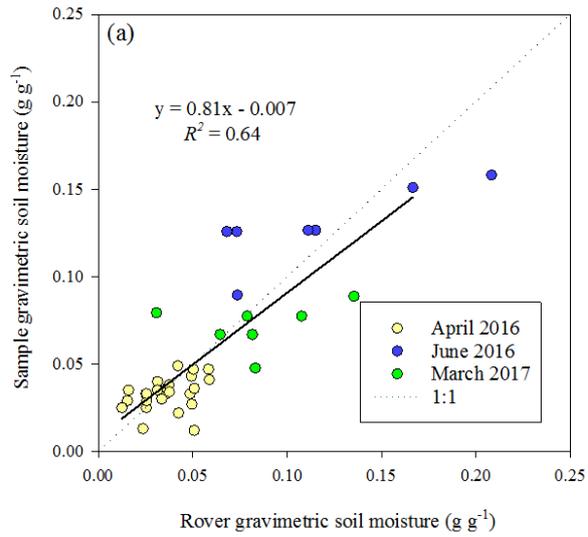
Figure 13. Broad scale rover survey gravimetric soil moisture (9 km resolution) versus point sample gravimetric soil moisture (a) and broad scale rover survey soil moisture (9 km resolution) versus AWRA-L root zone soil moisture (5 km resolution).

Figure 14. 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.
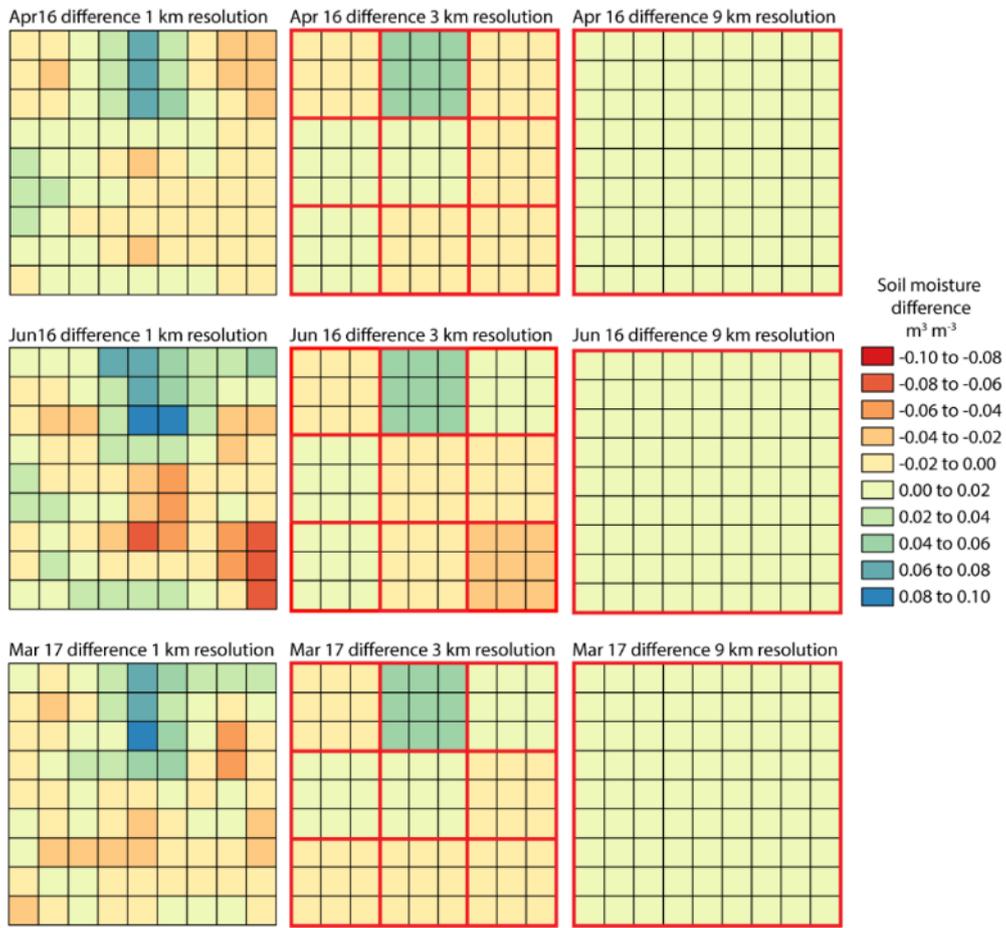
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754 **8   Appendix 1**

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

Property	Soil Moisture (m³ 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

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