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Interactive comment on "Calibration of a non-invasive cosmic-ray probe for wide area snow water equivalent measurement" *by* M. J. P. Sigouin and B. C. Si

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This study concerns the application of the cosmic-ray neutron method to monitor snow water equivalent. The authors performed neutron count measurements over two winters (2013/2014 and 2014/2015) in an agricultural field in Saskatoon (Canada). Based on this data, they developed an empirical equation to provide estimates of average SWE which were compared with continuous snow depth measurements.

This paper is an interesting presentation of a snow application of the cosmic-ray neutron method. It is also well written and fits well to the scope of Cryosphere Journal.

However, some methodological improvements need to be undertaken as outlined in my

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specific comments. In addition, I am not convinced that the presented method is able to provide quantitative estimates of SWE that are more accurate than the traditional snow depth measurements. Thus, the study should be more critical and should better discuss the potential drawbacks of the method.

Author response: Thank you for the excellent comments. As shown in our measured SWE data using snow tube, the point measurements are highly spatially variable. It is impossible to obtain accurate areal SWE without a large number of point measurements. Therefore, a point measurement of continuous snow depth can cause accuracy issues if wanting to upscale the measurement to represent a larger area. For example, melting can occur below the depth sensor or snow could preferentially accumulate around the depth sensor from wind redistribution. Thus, the CRP method should provide a better estimate of average SWE in the area since it does integrate over a larger area. As Anonymous Referee 1 mentioned, it is not very practical to compare the CRP accuracy to an array of continuous measurements since it is not common to have an intensive set up of continuous SWE measurement instruments in the field.

Unfortunately, the study suffers from the limited experimental setup. For instance, the temporal dynamics of snow depth and soil moisture within the CRP footprint should have been continuously monitored in a distributed way. In addition, the sampling design assumes a CRP footprint that is too large. Finally, the CRP used in this study shows a relatively high noise in neutron count rates. Thus, for future applications a CRP with a large detector tubes (e.g. CRS-2000/B) is preferable. These limitations and recommendations for future studies need to be discussed in greater detail.

Author's response: We agree that a continuous measurement of snow depth at our site would have been ideal, but our primary goal with our snow surveys was to capture the main temporal variation of the snowpack. We did our best effort to perform snow surveys immediately following snowfall events. Snow depth was continuously (daily) monitored at the research weather stations nearby the study site as we discussed in the paper. Monitoring soil moisture continuously during the study would be ideal, but we know that it will not vary significantly during the winter. If water does infiltrate the frozen soil it will likely not travel very far or form a basal ice layer at the soil surface.

The sampling design consisting of snow samples along 25, 75, and 200 m radials around the CRP was implemented prior to publication of the Kohli paper saying that the footprint is much smaller than 300 m. We re-did the regression as suggested by Reviewer 1 using only the SWE sampling points along the 25 and 75 m radials and found that the regression slope and intercept was similar to the first regression (which included 25, 75 and 200 m radials). Furthermore, the RMSE for the CRP-predicted SWE did not improve with the new regression using the nearest sampling points. This is because the variability of the SWE inside the 75 m radial is not different from the variability of SWE inside the 200 m radial. We added additional discussion regarding the footprint size in the manuscript discussion section.

Change in manuscript : Line 543 – 563 "In this study, the footprint of the CRP was assumed to be ∼300 m based on original studies using the CRP for soil water content measurements (Desilets and Zreda, 2013). Recent evidence displays that the CRP footprint might range from 130 – 240 m depending on soil water content and that a horizontal weighting function is needed to compare CRP measurements to other point measurements (Köhli et al., 2015). With an assumed footprint of ∼300 m, snow samples along 25, 75, and 200 m radials around the CRP were included in our calibration and validation of CRP-estimated SWE. Despite including the 200 m radial, the calibration provided acceptable estimates of SWE with the CRP when compared to snow surveys, which also included samples from the 200 m radial. The linear regression and calibration was redone using only the snow samples from the 25 and 75 m radials, but the regression slope and intercept was similar to the original regression (SWE samples from 25, 75, and 200 m radials). Furthermore, the RMSE of the CRP-estimated SWE did not improve when using the 25 and 75 m radial calibration. The characteristics of the study site is most likely the reason why including the 200 m radial for calibration and assuming a larger footprint (300 m) provided similar results as the calibration without the samples from the 200 m radial. The study site is flat and relatively bare of vegetation (short crop stubble evenly throughout field) causing the variability of SWE to be similar throughout the entire site. Using radials closer to the CRP when calibrating for SWE measurements would likely be necessary in other sites where vegetation or topography causes SWE distribution to be distinctly heterogeneous. For example, if the CRP was located in a depression where greater amounts of snow accumulated around versus further away from the probe."

We agree that a CRP with larger detector tubes should be used for future applications, but this work also demonstrates that SWE can be estimated from neutron counts by CRS-1000/B models already installed in the field throughout the COSMOS network. In order to reduce the noise in our neutron counts we increased the neutron count averaging to 13 hours.

Changed in manuscript: Line 270 - 274 "The corrected moderated neutron counts were then averaged over 13 hours. A 13-hour running average was used for the moderated neutron intensity counts in order to reduce the inherent noise of the hourly moderated neutron data and reduce measurement uncertainty, yet still allow responses to precipitation events to be observed (Zreda et al., 2008). For future studies, a CRP with larger detector tubes, such as the CRS-2000/B, should be used to further reduce the neutron intensity noise."

Specific comments (manuscript version)

L56: "Canada" instead of "CAN"

Changed in manuscript: Line 56 "...Saskatchewan, Canada."

L114: According to a recent study the footprint is considerably smaller and not constant in time, see Köhli et al. (2015)

Author reply: At the time of this study, the CRP footprint was consistently thought to be ∼300 m thus our methods were based on this larger estimated footprint. We acknowledged in the revised manuscript that there is slight controversy over the footprint size with the recent work by Köhli et al. (2015).

Changed in manuscript: Line 120 – 122 “Firstly, it has a landscape scale measurement area with a radius originally thought to be ∼300 m (Desilets and Zreda, 2013), but recently estimated to be ∼200 m (Köhli et al., 2015).”

L152-154: You should make some rough calculations how much the additional snow accumulation in the CRP footprint could have influenced the SWE estimates by the CRP. If the effect is in the sub-millimeter range it could be considered to be negligible.

Author reply: SWE Samples taken along the irrigation line were generally 50 to 70 mm greater than samples not along the line. Also, the snowdrift along the line melted far slower than the snowpack throughout the rest of the field because of the greater snow accumulation along the line.

L175: More details on the local soil properties need to be given (e.g. bulk density, porosity, soil texture, etc.).

Changed in manuscript: Line 164 “according to past soil surveys, the texture of the site is silt loam”

Line 211 – 214 “The average bulk density and total porosity from the 0 – 30 cm soil samples were 1.31 g cm-3 and 0.51 cm3 cm-3, respectively. For the top 10 cm, the average bulk density and total porosity were 1.01 g cm-3 and 0.61 cm3 cm-3, respectively. Organic matter and crop residue incorporated into the soil caused the lower bulk density in the top 10 cm of the soil at the site.”

L178-179: This is a very rough estimate and very likely prone to overestimation since vertical water transport into deeper soil region is neglected.

Author reply: We did not consider deep vertical water transport when estimating water storage since the fine soil texture (silt loam) at our site would lead to very slow drainage rates. If our site was coarser in nature then overestimation might be more pronounced.

L184: The value of 4.53 cm suggests that the soil porosity must be at least 0.453. This is extremely high, e.g. sandy soils have typically porosities in the range of 0.30-0.35 (Nimmo, 2004). Thus, this value is may be overestimated (see comment above).

Author reply: The soil at our site has a fine texture (silt loam) and the top 10 cm of the soil profile had crop residue from previous years incorporated into the soil surface. The fine texture and crop residue caused the bulk density for 0 – 10 cm to be 1.01 g cm-3 and the total porosity to be 0.61 cm3. This porosity would allow the value of 4.53 cm to be relevant.

L225-229: Such scaling is unnecessary in the case of this study. Scaling would be necessary in case absolute neutron count rates would be important, e.g. in case neutron count measurements from different locations would be compared among each other. However, in this study the neutron counts are converted to snow water equivalents, which is inherently a sort of scaling.

Author response: We will remove this scaling from the final corrected neutron counts.

Changed in manuscript: Line 259 – 263 "The corrected moderated neutron counts were then averaged over 13 hours. A 13-hour running average was used for the moderated neutron intensity counts in order to reduce the inherent noise of the hourly moderated neutron data and reduce measurement uncertainty, yet still allow responses to precipitation events to be observed (Zreda et al., 2008)."

L240: This spacing is not appropriate (see comment L114). Add a discussion on the consequences.

Author reply: We developed this study before the Köhli et al. (2015) paper came out so we used the spacing of 25, 75, and 200 m based on the original soil sampling schemes for the CRP when a footprint of 300 m was assumed.

Changed in manuscript: Line 270 "This sampling scheme is based on a CRP footprint of ∼300 m radius. According to Köhli et al. (2015), the CRP footprint might be smaller

(∼200 m radius). This study was performed prior to the new estimations of the CRP footprint so a radius of ∼300 m was still assumed and samples along the 200 m radial were included in the snow surveys.”

L256-259: How did your snow height and SWE data compare with predictions of this equation?

Author reply: Our measurements of snow depth and SWE closely matched predictions with the equation proposed by Shook and Gray (1994). We did not include figures showing the comparison between our sampled SWE and predictions based on snow depth because our CRP predicted SWE matched closely to our sampled SWE. Thus it would be as though we were displaying the same info twice on the figures where we compare our CRP-predicted SWE and snow depth estimated SWE.

L296: You should also present scatter-plots of the correlations (without the soil water storage adjustment).

Author reply: We included the correlation of neutrons and SWE without the soil water storage offset in Figure 3.

L321-324: This is very unlikely, since modelling of neutron transport of nonhomogeneous environmental conditions have shown that only extreme cases, e.g. discrete objects like tree trunks, may have an influence on neutron intensity (e.g. Franz et al., 2015). In any case, such assumptions would need to be substantiated by a dedicated neutron transport modelling study.

Author reply: We do not have neutron transport simulations to back up our statement regarding the penetration of neutrons in snow so we will remove our claim.

Changed in manuscript: Line 376 -377 “However, we observed a CRP response to SWE values of greater than 70 mm, when including antecedent soil water in the upper soil profile, during the 2014/15 winter. It is not completely clear why distinct CRP responses occurred at SWE values greater than 70 mm.”

L353: See earlier comments.

Author reply: Because of the fine soil texture and crop residue, the porosity was quite high in the top of the soil profile. This makes our soil water storage adjustment reasonable.

L364: How do these error estimated compare with traditional SWE measurement methods?

Author reply: The standard and most common SWE measurement method is snow tube measurements. Since our CRP predicted SWE is calibrated from snow tube measurements we cannot compare the CRP errors to snow tube errors. The second most common SWE measurement method is most likely snow pillow measurements. However, snow pillows work best in deep snowpacks, and do not work relatively well in shallow snowpacks such as the Canadian Prairies (the location of this study) as mentioned in the introduction. Since the only other non-point scale SWE measurement method is remote sensing, we compared our error values to a global remote sensing project aimed at measuring SWE called GlobSnow.

Changed in manuscript: Line 433 – 438 "The 2014/15 CRP-estimated SWE errors are considerably lower compared to other large-scale SWE measurement methods such as remote sensing. Large-scale (25 km resolution) remotely sensed SWE measurements using microwave radiation for the GlobSnow project (Luojus et al., 2010; Dietz et al., 2012) had RMSE values ranging from 24 to 77 mm when compared to snow courses."

L348: Fig. 5 clearly shows that the 7-hourly averaged neutron count rates are still strongly fluctuating. The reason for the strong fluctuations is the decreased sensitivity of the CRP due to the high hydrogen content in the CRP footprint. The sensitivity of the CRP can be easily increased by increasing the aggregation period, see Bogena et al. (2013) for a detailed analysis. I suggest using at least daily averaging to reduce the effect of CRP noise on the regression analysis.

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Author reply: We increased the running average to 13 hours since the snowpack can undergo significant changes during 24 hours from sublimation or snowfall events leading to large variations of neutrons throughout the day.

L377-378: Any snow melt water, especially above the soil surface, will lead to overestimation of SWE.

Changed in manuscript: Line 450 – 452 "Any snowmelt water that infiltrated or remained on the very top portion of the soil profile would affect the moderated neutron intensity, thus causing the CRP to estimate greater amounts of SWE."

L387: "Comparison of. . ."

Changed in manuscript: Line 461 "3.4 Comparison of CRP and snow depth estimated SWE"

L396: "estimated" instead of "modeled"

Changed in manuscript: Line 470 "CRP-estimated SWE"

L401: "SWE dynamics"

Changed in manuscript: Line 475 "Looking at Figure 6, it can be seen that SWE dynamics for both winters at the SRC and Saskatoon Airport RCS sites are quite close to the CRP-estimated SWE."

L408: See comment L152-154. In addition, this would only explain the overestimation of the first period.

Author reply: The snowdrift along the irrigation line did not melt the same as the rest of the field because of how much snow accumulated. Thus, there was consistently higher SWE along the irrigation line even after the melt periods.

L412-413: Although the distance between the RCS and Airport sites is far larger than the distance between the RCS and CRP sites, the point measurements at the RCS and

Airport sites seems to compare better. Also the point measurements seems to better compare with the manually measured SWE (please provide RMSE). This is even more notable, given the typically large spatial heterogeneity of snow covers. This suggests to me that the presented method less accurate as the point measurements, although the CRP method integrates over a larger area.

Author reply: Since the SRC and Airport sites are in different locations from the study site with slightly different surrounding vegetation and landscapes we cannot quantitatively compare the SWE between all three sites. We expect there to be differences between all of the sites. Our goal was not to compare accuracy of measurement between the snow depth SWE estimates from SRC/Airport sites and our CRP-estimated SWE since there are many factors that could cause differences in the SWE values such as differences in vegetation, landscape, and varying wind redistribution. The difference in locations causes us to only be able to compare the SWE dynamics between the sites.

Figures

Figure 1: A small-scale map should be included showing the location of the test site. The actual CRP footprint is smaller (see Köhli et al., 2015).

Author response: We included a small-scale map showing the main study site, and the two sites where snow depth measurements were used to estimate SWE.

Figure 2: The accumulated precipitation of the lower graphic is not correct (starts too late)

Author response: We removed the accumulated precipitation in order to improve the clarity of the figures.

Figure 5: See comment above. I suggest to remove the accumulated precipitation for the sake of better clarity.

Author response: Similar to the edit on Figure 2, we will remove the accumulated precipitation to improve the figure.

Literature

Bogena, H., Huisman, S., Baatz, R., Hendricks Franssen, H.-J. & Vereecken, H. 2013. Accuracy of the cosmic-ray soil water content probe in humid forest ecosystems: The worst case scenario. Water Resources Research, 49, 5778-5791.

Franz, T.E., Zreda, M., Rosolem, R., Hornbuckle, B.K., Irvin, S.L., Adams, H., Kolb, T.E., Zweck, C. & Shuttlewort, W.J. 2013. Ecosystem-scale measurements of biomass water using cosmic ray neutrons. Geophysical Research Letters, 40, 3929-3933.

Köhli, M., Schrön, M., Zreda, M., Schmidt, U., Dietrich, P. & Zacharias, S. 2015. Footprint characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons. Water Resources Research, 51, doi: 10.1002/2015WR017169.

Nimmo, J.R. 2004. Porosity and Pore Size Distribution, in Hillel, D., ed. Encyclopedia of Soils in the Environment: London, Elsevier, v. 3, p. 295-303.

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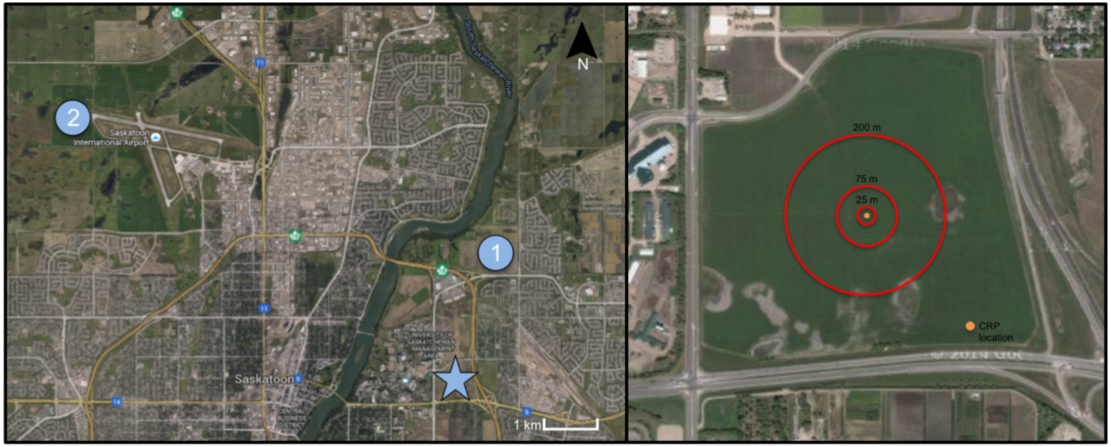

Fig. 1. Revised Figure 1

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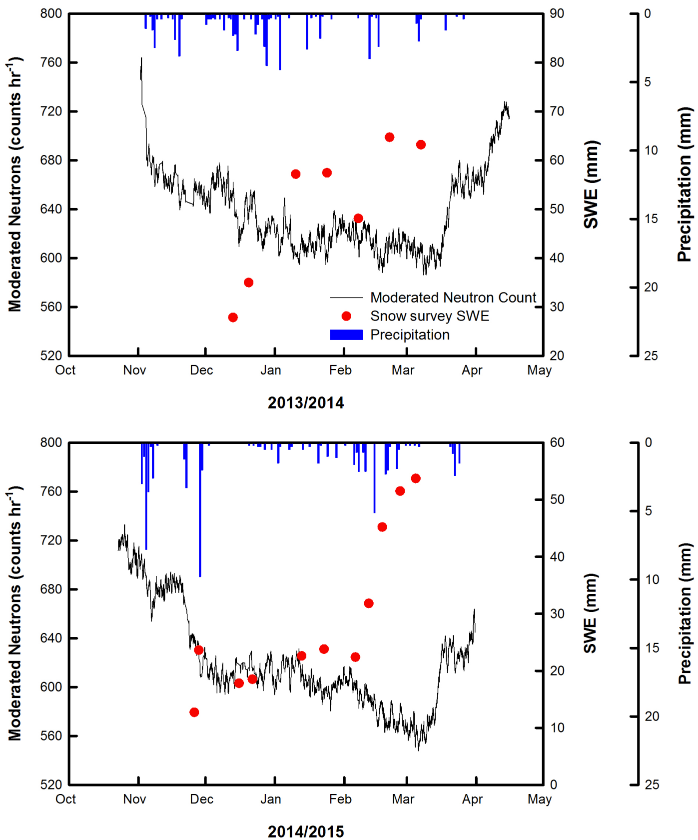

Fig. 2. Revised Figure 2

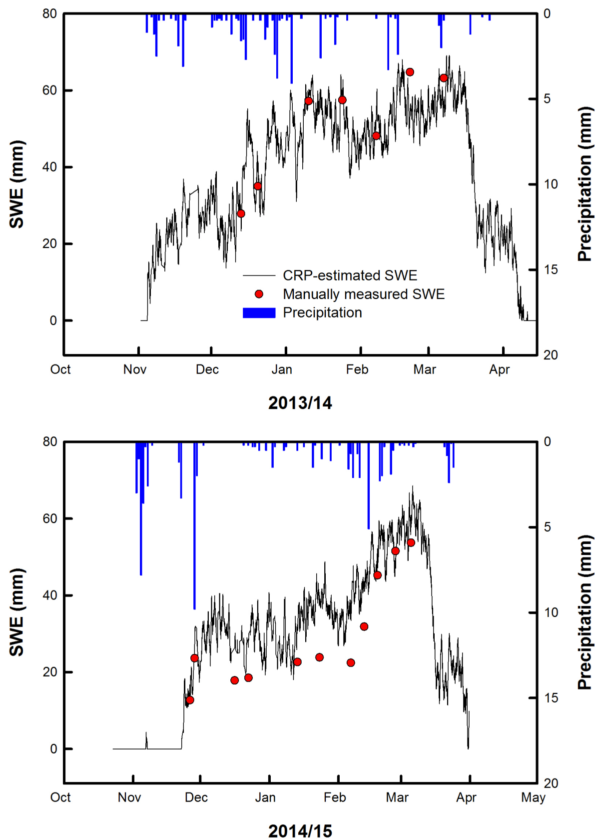

Fig. 3. Revised Figure 5

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