Calibration of a non-invasive cosmic-ray probe for wide area snow water equivalent measurement

Author Response to Comments:

Anonymous Referee #1:

General Comments

This work discusses the use of a non-invasive cosmic-ray sensor for measuring snow water equivalent (SWE) and provides a calibration function that applies to shallow snow packs. The technology is relatively new. The same type of sensor has been used for monitoring soil moisture in a number of countries, starting with the COSMOS network in the US, since around 2006. To my knowledge this is the first SWE calibration that has been submitted for publication. These results will enable the use of COSMOS data (and data from other networks) for monitoring winter SWE in addition to summer soil moisture. I believe this work to be highly valuable through its demonstration and advancement of new technology that will benefit snow hydrologists.

Author reply: We appreciate the excellent comments.

Specific Comments Line 319-322: I am fairly sure that there is no density or porosity effect based on my knowledge of physical principles (and also modeling and empirical results). It's really the number of collisions that matter–i.e. the number of collisions that a neutron will experience as it passes through the snow pack. The distance between collisions will increase as density decreases, but the total effect is exactly the same. However, if you want to stick with this explanation I would suggest starting the sentence with "We speculate that..."

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 speculation.

Line 591: (Figure 3) I don't see any value in the combined regression as it is done here, given the evidence for an offset. Hence in order to "combine" the two seasons of data, one season should be normalized to the other, and then the linear regression performed. Or the regression coefficients (slopes and intercepts) might simply be averaged between the two seasons. I am not sure which is better; but should not matter anyhow since the slopes are nearly the same.

Author reply: We agree that the combined regression in Figure 3 does not give significant value. With the offset applied to the 2014/15 data, the slope is similar to the 2013/14 regression thus the combined regression really does not add much value. We will remove the combined regression since we used the regression from 2013/14 (not the combined regression) for estimating SWE for 2014/15.

Line 352-364: The first half of this paragraph is a bit awkward. I think the most relevant part is the last two sentences of the paragraph; before that the author seems caught in a circle. I think it can be explained like this: the author collected two seasons of calibration data, and the RMSE for each season was ___.

Author reply: We edited the mentioned paragraph to be more concise and focus on the RMSE of the 2014/15 CRP-estimated SWE.

Changed in manuscript: Line 434 – 440 "For both winters, the CRP-estimated SWE match the manually measured SWE well. Of course for 2013/14 the manually measured SWE corresponds nicely to the CRP-estimated SWE since the regression equation from 2013/14 was used for SWE prediction. The CRP-estimated SWE for 2014/15 also agrees with manually measured SWE. The root-mean-squared error (RMSE) and mean absolute error for the 2014/15 CRP-estimated SWE is 8.8 and 7.5 mm, respectively. These error results are comparable to Rasmussen et al. (2012), who found an RMSE of 5.1 mm between SWE estimated from snow depth and from a CRP."

Technical Comments

Line 52: replace "measurement scale" with "spatial scale" (word measurement is redundant in this sentence)

Change in manuscript: Line 51-53 "We explored the potential of using the cosmic-ray soil moisture probe (CRP) to measure average SWE at a spatial scale between those provided by snow tubes and remote sensing."

Line 65: delete "very"

Change in manuscript: Line 65 "...measured SWE and moderated neutron counts were similar, thus differences in antecedent..."

Line 86: insert "field survey" between "common" and "method" (I am not sure what is the most common method overall, but it seems uncontroversial that the snow tube is the most common method for campaign style surveys.)

Changed in manuscript: Line 89 "...most common field survey method for determining SWE and although it provides a point..."

Line 88: importantly, snow tubes are prone to systematic errors, the magnitude and direction of which depends on snow conditions. At least that is what this reviewer has observed; I wish I had a better reference than that handy.

Changed in manuscript: Line 91-92 "...However, snow surveys with snow tubes are labour intensive, can be difficult to perform in remote locations, and are prone to over- and underestimation of SWE depending on snowpack conditions (Goodison, 1978)."

Line 110: cite Desilets et al. (2010) with regard to the potential to measure SWE.

Changed in manuscript: Line 116 "...but also has the potential to be a useful tool for measuring SWE (Desilets et al., 2010)."

Line 114: delete "the" at end of line.

Changed in manuscript: line 126 "...capable of measuring neutrons moderated by hydrogen in snow, i.e. frozen water."

Line 128: add "and the Pyrenees of Spain" after the word "France".

Changed in manuscript: Line 135 "...probes in France and the Pyrenees of Spain (Paquet et al., 2008)."

Line 141: delete everything after word "site". (These extra words are superfluous.)

Changed in manuscript: Line 150 "...from multiple locations around the study site."

Line 154: "increased accumulation of snow along the line" for clarity

Changed in manuscript: Line 163 "...causing increased snow accumulation along the line, but the irrigation line was removed..."

Line 163: this is a good place to explain why you only analyze data from the mod tube. You could end the first sentence by saying something like "...following the practice established for soil moisture observations (Zreda et al., 2012)." Relationships between the bare tube counting rate and SWE are thought to be less straightforward.

Changed in manuscript: Line 173 – 178 "Slow neutrons are affected by more than just H, including other neutron absorbing elements in soil such as B, Cl, and K (Desilets et al., 2010). Also, the relationship between the bare tube counting rate and SWE are thought to be less straightforward than the moderated neutron and SWE relationship. Thus, only the moderated neutron count was used in this study following the practice established for soil moisture observations (Zreda et al., 2012)."

Line 187: start sentence with "The raw neutron..." (i.e. delete everything before that)

Changed in manuscript: Line 208 "The raw neutron counts must be corrected for differences in air pressure, atmospheric water vapor, and the temporal variation of incoming cosmic ray flux."

Line 205: (1) For consistancy in units, convert g cmˆ-2 to hPa (130.24 * 0.9807 = 127.5 hPa). (2) Round to one decimal place or less (higher precision is not justified or needed).

Changed in manuscript: Line 226 – 228 "*L* represents the mass attenuation length (hPa), which is a function of latitude and atmospheric depth (Desilets and Zreda, 2003). The mass attenuation length for Saskatoon was found to be 127.5 hPa."

Line 247: insert words "a first order" (or something with similar meaning) between "for" and "comparison".

Changed in manuscript: Line 272 "Snow depth data from two reference sites were used for a first order comparison to the snow surveys and CRP data."

Line 301: delete word "regression" which is redundant.

Changed in manuscript: Line 326 "Initial regressions showed that both 2013/14 and 2014/15 had similar slopes but quite different intercepts."

Lines 305-306: please clarify by saying that the intercepts of the regression lines match up more closely. (at least I think you mean the intercepts).

Changed in manuscript: Line 331 – 332 "The added soil water storage caused the intercept of the 2014/15 regression line to match more closely with the intercept for 2013/14."

Line 324: instead of saying "and simple regression was completed" say something like "and fitted with a linear regression model"

Author reply: This sentence was removed from the manuscript because we removed the combined regression.

Line 332: delete "simple" (superfluous)

Changed in manuscript: Line 361 "...thus linear regression was used for modeling SWE from moderated neutrons."

Line 337: no need to show this equation both here and on Line 348.

Changed in manuscript: Line 366 – 367 "The best-fit linear regression equation for the 2013/14 data produced an r^2 of 0.84."

Line 394: replace "fully" with "quantitatively"

Changed in manuscript: Line 425 – 426 "It is difficult to quantitatively compare the snow depth results to the CRP-modeled SWE since..."

Line 422: replace "regards" with "regard"

Changed in manuscript: Line 454 – 456 "Overall, the presented equation performed favourable with regard to providing an estimate of average field SWE at this agricultural study site."

H. Bogena (Referee) h.bogena@fz-juelich.de Received and published: 27 January 2016
General comments

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 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 cm^3 cm^{-3}, respectively. For the top 10 cm, the average bulk density and total porosity were 1.01 g cm^{-3} and 0.61 cm^3 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 cm^3. 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 nonhomogenous 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.

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.

G. Baroni gabriele.baroni@ufz.de Received and published: 29 February 2016

Dear Authors,

I take the chance of the open discussion provided by the Journal for adding a short comment. I hope this could help for further improving of the manuscript. We have experienced the use of Cosmic-Ray neutron sensing (CRNS) since 2010. Our studies focused mainly on soil moisture measurements. However the role of snow was also detected and a preliminary concept for possible quantification was provided (see fig. 9 in Rivera Villarreyes et al., 2011). After that experience, we realized that CRNS has several opportunities to estimate not only soil moisture. For this reason we put some efforts to show the possibility to identify additional hydrogen pools (Baroni and Oswald, 2015). Similarly, I believe that also your contribution for snow estimation is a valuable and important study to explore new applications.

Author reply: Thank you for mentioning the study by Rivera Villarreyes et al. (2011). We included a reference to the relationship found in fig. 9 of Rivera Villarreyes et al. (2011).

Changed in manuscript: “Additionally, Rivera Villarreyes et al. (2011) observed the possibility to measure snow with neutron counts from a CRP (model CRS-1000), but only explored the relationship between neutron counting rates and snow cover instead of SWE.”

Independently from the target of the study (soil moisture, snow etc.), I think one of the main challenge that we are facing now for the applicability of the method is the characteristics of the footprint. The temporal variability of the penetration depth of the CRNS as a function of hydrogen pools was already underlined in the earlier publication (Zreda et al., 2008). The need of a vertical weighting function was developed later (Franz et al., 2012). Recently, Köhli et al. (2015) showed that also the spatial footprint shrinks in space and a spatial weighting function is also needed. Overall we have to take into account that the water estimate by CRNS is a weighting value within a footprint that changes in time. So far the studies focused on soil moisture but we could expect that the same happens in snow conditions. One could even speculate that the role of snow could be even stronger i.e., smaller footprint and stronger time variability. Exactly for this reason I would suggest the Authors to include in the analysis a spatial and vertical weighting function for the point snow measurements. The same comment was underlined by the Reviewers (e.g., Reviewer 1: the author should then recalculate the regression using only the nearest points, and see if the regression improves) but I write to emphasis that a time dependent weighting function (horizontal and vertical) might also be necessary i.e., the weights might change in each campaign.

Author Response: We agree that the CRP reading is a weighted horizontal measurement. Similar to the depth weighting function provided by Franz et al. (2012), a horizontal weighting function might also be necessary in environments where snow distribution is distinctly heterogeneous (i.e. rolling landscape with more snow accumulation closer to the CRP). We did redo the regression with only using the sampling points along the 25 and 75 m radials, and found that the regression slope and intercept was similar to the previous regression including all radials (25, 75, 200 m). Also, the RMSE of the CRP-predicted SWE did not improve when using the new 25 and 75 m radial regression. The reason that we did not see an improvement from using only the nearest points to the CRP is most likely because our site is a flat, bare (except for short crop stubble) agriculture field causing the SWE distribution to be relatively homogenous. We included a short discussion of the possible need for a weighted horizontal function in sites that are more heterogeneous in terms of landscape and vegetation.

Changed in manuscript: Line 490 – 511 "3.5 Footprint for CRP-estimated SWE

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."

A small final remark is also that I did not find information about the altitude of the experimental site. Since this effects the dimension of the footprint (more precisely by the relation between altitude and air pressure) I would suggest the Authors to provide additional information and in case to extend the discussion. For an estimation of the footprint as a function of pressure see eq. 21 on (Desilets and Zreda, 2013).

Author reply: We added a short discussion regarding the footprint size based on altitude/air pressure at our site.

Changed in manuscript: Line 174 "The altitude and average air pressure of Saskatoon are 482 m and 955 hPa, respectively. According to Desilets and Zreda (2013) the measurement footprint of the CRP changes slightly based on air pressure of the site. Air pressure affects the neutron moderation length, which controls the footprint of the CRP. Using Eq. 21 from Desilets and Zreda (2013) and sea level as a reference (moderation length = 150 m, air pressure = 1013 hPa), the moderation length for Saskatoon was found to be 141 m. The radius of the CRP footprint is 2 times the moderation length. Therefore, the site-specific CRP footprint for Saskatoon has a radius of 283 m."

In conclusion, I would suggest the Authors putting more effort on the analysis of the data and to extend the discussion accordingly. With these, the manuscript could represent more than an additional proof of concept on the use of CRNS for snow measurements but it could show some new insight on how to use the method for this application.

Author reply: Thank you very much for your valuable comments.

Best regards, Gabriele Baroni

Calibration of a non-invasive cosmic-ray probe for wide area snow water equivalent measurement

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Abstract

Measuring snow water equivalent (SWE) is important for many hydrological purposes such as modeling and flood forecasting. Measurements of SWE are also crucial for agricultural production in areas where snowmelt runoff dominates spring soil water recharge. Typical methods for measuring SWE include point measurements (snow tubes) and large-scale measurements (remote sensing). We explored the potential of using the cosmic-ray soil moisture probe (CRP) to measure average SWE at a spatial scale between those provided by snow tubes and remote sensing. The CRP measures above ground moderated neutron intensity within a radius of approximately 300 m. Using snow tubes, surveys were performed over two winters (2013/2014 and 2014/2015) in an area surrounding a CRP in an agricultural field in Saskatoon, Saskatchewan, Canada. The raw moderated neutron intensity counts were corrected for atmospheric pressure, water vapor, and temporal variability of incoming cosmic ray flux. The mean SWE from manually measured snow surveys was adjusted for differences in soil water storage before snowfall between both winters because the CRP reading appeared to be affected by soil water below the snowpack. The SWE from the snow surveys was negatively correlated with the CRP-measured moderated neutron intensity, giving Pearson correlation coefficients of -0.90 (2013/14) and -0.87 (2014/15). A linear regression performed on the manually measured SWE and moderated neutron intensity counts for 2013/14 yielded an r^2 of 0.81. Linear regression lines from the 2013/14 and 2014/15 manually measured SWE and moderated neutron counts were similar, thus differences in antecedent soil water storage did not appear to affect the slope of the SWE vs. neutron relationship. The regression equation obtained from 2013/14 was used to model SWE using the moderated neutron intensity data for 2014/15. The CRP-estimated SWE for 2014/15 was similar to that of

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the snow survey, with a RMSE of 8.8 mm. The CRP-estimated SWE also compared well to estimates made using snow depths at meteorological sites near (<10 km) the CRP. Overall, the empirical equation presented provides acceptable estimates of average SWE using moderated neutron intensity measurements. Using a CRP to monitor SWE is attractive because it delivers a continuous reading, can be installed in remote locations, requires minimal labour, and provides a landscape-scale measurement footprint.

Keywords: cosmic rays; snow water equivalent; moderated neutrons; landscape scale

1. Introduction

Landscape-scale snow water equivalent (SWE) measurements are important for applications such as hydrological modeling, flood prediction, water resource management, and agricultural production (Goodison et al., 1987). Particularly in the Canadian Prairies, snowmelt water is a critical resource for domestic/livestock water supplies and soil water reserves for agriculture purposes (Gray and Landine, 1988). Snow is also a key contributor in recharging Canadian Prairie wetlands, which provide important wildlife habitat (Fang and Pomeroy, 2009).

Common techniques for measuring SWE include snow tubes (gravimetric method), snow pillows, and remote sensing (Pomeroy and Gray, 1995). Snow tube sampling is the most common field survey method for determining SWE and although it provides a point measurement, can be used to survey a larger area. However, snow surveys with snow tubes are labour intensive, can be difficult to perform in remote locations, and are prone to over- and underestimation of SWE depending on snowpack conditions (Goodison, 1978). Snow pillows can provide SWE measurements in remote locations, but produce merely a point

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measurement of roughly 3.5 m^2 to 11.5 m^2 (Goodison et al., 1981). In addition, snow pillows do not accurately measure shallow snowpacks due to snow removal by wind transport and melting (Archer and Stewart, 1995). Remote sensing has the capability of measuring SWE at large scales based on the attenuation of microwave radiation emitted from Earth's surface by overlying dry snow (Dietz et al., 2012). The applicability of remote sensing techniques for SWE monitoring is limited by their coarse measurement resolutions (~625 km^2), their inability to accurately measure wet snow, and their shortcomings in measuring forested landscapes.

A measurement scale between that of the point measurements and the large scale remote sensing can be desirable due to the high variability in SWE that can occur even over small distances (Pomeroy and Gray, 1995). Shook and Gray (1996) found high variability in snow depth and water equivalent when performing snow surveys with samples every 1 m along transects in shallow snow covers in the Canadian Prairies. Variability of SWE at this small scale was attributed to differences in wind redistribution and transport, along with variations in surface roughness and micro topography. The high variability of SWE at smaller scales can lead to difficulty when trying to estimate average SWE in a field or catchment from a few point measurements. Instead, labour intensive snow surveys are generally required. At larger scales, spatial variability of SWE is generally a function of the differences in snowfall and accumulation from varying vegetation and topography (Pomeroy and Goodison, 1997).

The cosmic-ray soil moisture probe (CRP) is a relatively new instrument that was primarily developed for measuring average soil water content at the landscape scale (Zreda et al., 2008), but also has the potential to be a useful tool for measuring SWE (Desilets et al., 2010). The CRP measures neutrons in the fast to epithermal range, which are emitted from soil and inversely related to soil water content due to the neutron moderating characteristic of hydrogen (H). The CRP is an appealing soil water content measurement tool for several reasons. 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). Secondly, it measures soil water content passively (non-radioactive) and non-invasively (CRP sits above the soil surface). Thirdly, the CRP can be deployed easily in remote areas. Lastly, it provides a continuous measurement of average soil water content, often with a temporal resolution of one hour. The CRP measurement is based on the moderation of neutrons by hydrogen in water, therefore it is also capable of measuring neutrons moderated by hydrogen in snow, i.e. frozen water.

The possibility of measuring SWE from the moderation of neutrons by snow has been known since the late 1970s (Kodama et al., 1979), but studies have been limited. Kodama et al. (1979) used a cosmic-ray moderated neutron sensor buried beneath the snow to measure SWE. Although their results showed a promising relationship between moderated neutron counts and SWE, the fact that the moderated neutron measuring tube was installed beneath the snowpack resulted in merely a point measurement. Others have successfully used cosmic-ray probes buried under snowpacks to measure SWE, including a network of buried probes in France and the Pyrenees of Spain (Paquet et al., 2008). Desilets et al. (2010) compared SWE values measured with a CRP installed above-ground to that of SWE values measured manually with a snow tube at the Mt. Lemmon Cosmic Ray Laboratory, Arizona. However, the CRP was installed within a laboratory, and Desilets et al. (2010) provided limited details of their study and did not include the relationship they utilized for deriving SWE from measured moderated neutron counts. Using a CRP to monitor SWE was also tested at the Marshall Field Site, Colorado, USA (Rasmussen et al., 2012). Again, limited details were given

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on the methods of the study and the empirical relationship used to predict SWE from moderated neutron intensity. Additionally, Rivera Villarreyes et al. (2011) observed the possibility to measure snow with neutron counts from a CRP (model CRS-1000), but only explored the relationship between neutron counting rates and snow cover instead of SWE.

The purpose of this study was to establish a simple empirical relationship between SWE and moderated neutrons measured above a snowpack using a CRP. Average SWE in an agricultural field was predicted from CRP moderated neutron measurements using relationship developed in this study between SWE and moderated neutrons. Predicted SWE from CRP measurements was compared to manual snow surveys and snow precipitation data from multiple locations around the study site.

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2. Methods

2.1 Site description and site-specific CRP footprint

This work was performed at an agricultural field (52.1326 °N, 106.6168 °W) located near the University of Saskatchewan in Saskatoon, Saskatchewan, Canada. The field covers roughly 46 ha and is approximately rectangular in shape. This study site was primarily chosen because the estimated measurement footprint of the CRP would fall within the boundaries of the field. The topography of the site is relatively flat and according to past soil surveys, the texture of the site is silt loam. The field is mostly free from trees and vegetation except for a small cluster at its south edge and the crop stubble that was left after harvest in the fall of each study year. The same study site was used for both (2013/14 and 2014/15) winter field seasons. Wheat stubble (height ~20 cm) was present on the field for the 2013/14 winter, and canola stubble (height ~25 cm) for the 2014/15 winter. Also, a set-move wheeled irrigation line

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was located across the center of the field during the 2013/14 winter causing increased snow accumulation along the line, but the irrigation line was removed before the 2014/15 winter.

The altitude and average air pressure of Saskatoon are 482 m and 955 hPa, respectively. According to Desilets and Zreda (2013) the measurement footprint of the CRP changes slightly based on air pressure of the site. Air pressure affects the neutron moderation length, which controls the footprint of the CRP. Using Eq. 21 from Desilets and Zreda (2013) and sea level as a reference (moderation length = 150 m, air pressure = 1013 hPa), the moderation length for Saskatoon was found to be 141 m. The radius of the CRP footprint is 2 times the moderation length. Therefore, the site-specific CRP footprint for Saskatoon has a radius of 283 m.

2.2 CRP and background water content

The model of CRP used in this study was a CRS-1000/B (Hydroinnova, NM, USA). This model consists of two neutron detector tubes and an Iridium modem data logger for remote data access. One of the detector tubes is shielded (or moderated) to measure neutrons of slightly higher energy (epithermal to fast range) and one tube is unshielded to measure lower energy neutrons (slow neutrons). The neutrons detected by the moderated tube in the epithermal to fast range are referred to as moderated neutrons. Slow neutrons are affected by more than just H, including other neutron absorbing elements in soil such as B, Cl, and K (Desilets et al., 2010). Also, the relationship between the bare tube counting rate and SWE are thought to be less straightforward than the moderated neutron and SWE relationship. Thus, only the moderated neutron count was used in this study following the practice established for soil moisture observations (Zreda et al., 2012). An in-depth description of how the CRP measures neutrons can be found in Zreda et al. (2012). The CRP was installed in the center of

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the field site (Figure 1) from the end of October 2013 until after snowmelt in the spring of 2014 (2013/14 winter). Similarly, for the 2014/15 winter, the CRP was installed in the same location and again collected data until snowmelt in spring of 2015. After installation of the CRP and before the first snowfall event of both winters, average soil water content within the CRP measurement footprint was measured manually from soil cores of known volume. The soil sampling scheme was as follows: 18 total sampling locations comprised of 6 locations evenly spaced along each of 3 radials spanning outward of the CRP (25 m, 75 m, and 200 m). Each location was sampled in 5 cm increments to a depth of 30 cm. This sampling scheme follows the typical method for calibrating CRPs for measuring soil water content (Franz et al., 2012b). Volumetric water content was measured from the cores via the oven-drying method (Gardner, 1986). The average bulk density and total porosity from the 0 – 30 cm soil samples were 1.31 g cm^{-3} and 0.51 cm^{3} cm^{-3}, respectively. For the top 10 cm, the average bulk density and total porosity were 1.01 g cm^{-3} and 0.61 cm^{3} 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.

The soil water storage in the top 10 cm of the soil profile, prior to snowfall, was estimated for both winters from the measured average soil water content and precipitation data. Precipitation data was collected from a Saskatchewan Research Council (SRC) climate station (52.1539 °N, 106.6075 °W) located near the study site. Rainfall events recorded after soil sampling, but before the appearance of the snowpack, were added to the antecedent soil water storage. It was assumed that all of the water from rain events before snowfall entered the soil and evapotranspiration was negligible due to the low air temperatures. The soil water storage in the top 10 cm of the soil profile was 2.15 cm in 2013 and 4.53 cm in 2014, creating

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a difference of 2.38 cm in water storage between the beginnings of the 2013 and 2014 winters.

Approximate location of Figure 1.

2.3 Raw moderated neutron correction

The raw neutron counts must be corrected for differences in air pressure, atmospheric water vapor, and the temporal variation of incoming cosmic ray flux. Corrected neutron counts are attained from multiplying the raw counts by correction factors:

$$N_{COR} = N_{RAW} \cdot F_p \cdot F_w \cdot F_i \qquad (1)$$

where N_{COR} is the corrected moderated neutron count, N_{RAW} is the raw moderated neutron count, F_p is the air pressure correction factor, F_w is the atmospheric water vapor correction factor, and F_i is the variation of incoming cosmic-ray flux correction factor.

Correcting for differences in air pressure is important since the incoming cosmic-ray flux is attenuated with increasing nuclei present in the atmosphere i.e. as air pressure increases (Desilets and Zreda, 2003). F_p is calculated with the following equation:

$$F_p = e^{\left(\frac{P-P_0}{L}\right)} \qquad (2)$$

where e is the natural exponential. P is the measured air pressure (hPa) at the site during the moderated neutron count time. Air pressure was measured near the CRP using a WeatherHawk 232 Direct Connect Weather Station (WeatherHawk, UT, USA). P_0 is a reference air pressure chosen to be 1013 hPa (average sea-level air pressure). L represents the mass attenuation length (hPa), which is a function of latitude and atmospheric depth (Desilets and Zreda, 2003). The mass attenuation length for Saskatoon was found to be 127.5 hPa.

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Since neutron counts are mainly related to the amount of hydrogen molecules in an area, raw moderated neutron counts must also be corrected for differences in atmospheric water vapor. Rosolem et al. (2013) found the following correction function for atmospheric water vapor:

$$F_w = 1 + 0.0054 \cdot (p_{v0} - p_{v0}^{ref}) \quad (3)$$

where p_{v0} is the absolute humidity (g m^{-3}) at the site during the measurement time. p_{v0}^{ref} is the reference absolute humidity and was set to that of dry air (0 g m^{-3}). Relative humidity and air temperature, which are both used to calculate absolute humidity, were measured at the site using the WeatherHawk weather station.

Correcting for the temporal variation of the cosmic-ray flux is the final correction for the raw neutron counts. This correction is performed using counts from neutron monitors along with the following equation:

$$F_i = \frac{N_{avg}}{N_{nm}} \quad (4)$$

where N_{avg} is the average neutron monitor count rate during the study period and N_{nm} is the specific hourly neutron monitor count rate at the time of interest. Data from the neutron monitor at Fort Smith (60.02 ° N, 111.93 ° W), Canada, was used in this study. The Fort Smith data was obtained from the NMDB database (www.nmdb.eu). 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

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detector tubes, such as the CRS-2000/B, should be used to further reduce the neutron intensity noise.

2.4 Snow surveys

Snow surveys were performed periodically in the field each winter within the estimated CRP measurement footprint. During the 2013/14 winter, seven surveys consisting of 18 sampling points were completed. Throughout the 2014/15 winter, eleven surveys composed of 36 sampling points were performed. The SWE sampling points were evenly spaced along each of the individual soil sampling radials, 25, 75, and 200 m, away from the CRP. 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. The sampling radials are unevenly spaced away from the CRP to allow for the calculation of a simple arithmetic mean of SWE based on the non-linear decreasing sensitivity of the CRP with increasing distance away from the probe (Zreda et al., 2008). Snow cores were collected for SWE using a Meteorological Service of Canada (MSC) snow tube with an inner diameter of 7.04 cm. The cores were carefully transferred to plastic bags, sealed, and transported to the lab for processing. The depth of snow was measured in situ at each sampling location during the snow survey.

2.5 Snow depth data

Snow depth data from two reference sites were used for a first order comparison to the snow surveys and CRP data. These were the SRC site and Saskatoon Airport Reference Climate Station (RCS) site (52.1736° N, 106.7189° W), located approximately 2.4 and 8.2 km

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from the CRP. At both reference sites, snow depths were measured using a SR50 Sonic Ranging Sensor (Campbell Scientific, Canada). Manual readings with measuring sticks were also performed occasionally at the SRC site.

The snow depth data were converted to SWE values in order to compare to the snow surveys and CRP data. Shook and Gray (1994) studied shallow snow covers (less than 60 cm) in the province of Saskatchewan over 6 years and found the following linear relationship for predicting SWE from snow depth:

$$SWE = 2.39D + 2.05 \quad (5)$$

where *D* is snow depth in cm and *SWE* is in mm. Equation 5 was used to estimate SWE using the snow depth data from the two reference sites. Although the SRC and Saskatoon Airport RCS sites are located a few kilometers away from the study site, comparing estimated SWE from these reference sites to SWE estimated from the CRP is still useful if we look only at the overall trend of snow accumulation.

3. Results and Discussion

3.1. Snow surveys and moderated neutron intensity

Moderated neutron intensity recorded by the CRP and SWE from snow surveys are shown in Figure 2. According to the field snow surveys from both winters (2013/14 and 2014/15), the measured mean SWE peaked at 64.7 mm in 2013/14 and 53.7 mm in 2014/15. The SWE varied significantly throughout the field between individual sampling locations, despite the study site being relatively homogeneous. The standard deviation (STD) of SWE for the snow surveys ranged from 5.7 to 18.1 mm in 2013/14 and 2.5 to 10.7 mm in 2014/15. It should be noted that the final five mean SWE values for 2014/15 include the addition of a shallow ice layer that was observed along the soil surface, below the entire snowpack. The ice layer formed after a warm period near the end of January 2015 and was present at each SWE sampling location. The ice layer was too dense for the teeth of the snow tube to cut through, thus the depth of ice was recorded. An average ice layer depth of 1 cm was observed during the last 5 snow surveys. The ice water equivalent was calculated from an assumed density of 0.916 g cm^{-3}, found by Hobbs (1974) to be the average density of ice. A value of 9.2 mm was then added to the mean SWE measured during the final 5 snow surveys of 2014/15.

Early in both winters (early November), the moderated neutron intensity decreased quite drastically in response to the first snow events of the season. These results are consistent with Desilets et al. (2010) who, although did not have precipitation data, found that observed snowfall events caused quick decreases in moderated neutron intensity. The first cluster of precipitation events and first significant decrease in moderated neutron intensity in 2014/15 (Figure 2) represent rainfall events. The second distinct decrease in moderated neutron intensity, in late November 2014/15, was caused by snowfall events. In Figure 2, all of the precipitation events for 2013/14 were snowfall events.

In general, moderated neutron intensity shows an expected negative relationship with both precipitation events and SWE, resulting in decreased moderated neutron intensity and increased mean SWE in response to precipitation. A relatively strong negative correlation between mean SWE and the moderated neutron intensity at the time of snow survey can be seen from the Pearson's correlation coefficients -0.90 and -0.87 for 2013/14 and 2014/15, respectively. These correlations show there is potential for predicting SWE from moderated neutron intensity measured above the snowpack.

Approximate location of Figure 2.

3.2. Regression of moderated neutron intensity and SWE

Simple linear regression was performed on the manually measured SWE values and the corresponding moderated neutron intensity during the snow survey. Initial regressions showed that both 2013/14 and 2014/15 had similar slopes but quite different intercepts (Figure 3). The difference in intercepts was attributed to the differences in soil water storage in the upper soil profile prior to snowfall. The previously mentioned calculated difference in soil water storage in the top 10 cm of the soil profile of 23.8 mm was added to the SWE values of 2014/15 and linear regression was repeated. The added soil water storage caused the intercept of the 2014/15 regression line to match more closely with the intercept for 2013/14 as can be seen in Figure 3. This result indicates that the CRP reading is still being affected by water present in the upper soil profile despite the presence of a snowpack. Thus, knowledge of the initial or background soil water storage in the top of the soil profile before each winter is important for predicting SWE from moderated neutron intensity from year to year. However, the combined measurement depth of the CRP in the snowpack and underlying soil is not fully known. With no standing water covering the soil surface, the CRP measurement depth is thought to range from 70 cm (dry soil) to 12 cm (saturated soil) (Zreda et al., 2008). In pure water, Franz et al. (2012a) found the effective measurement depth to be ~58 mm (i.e. the CRP measurement becomes saturated when more than 58 mm of water is above the soil surface. The effective measurement depth is considered the depth at which 86% (two e-folds) of the measured neutrons originate assuming an exponential decrease in neutron intensity with

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depth. 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.

The individual regression curve for the 2013/14 data is shown in Figure 4 with the best-fit linear regression equation for the data producing an r^2 of 0.81. Due to the similarity between the regression lines for 2013/14 and 2014/15 with the soil water storage offset, the 2013/14 regression equation was used for estimating SWE in 2014/15. The similarity between the regression lines indicates that the slope of the model is not affected by differences in soil water storage near the soil surface. The linear regression and relationship of the SWE and moderated neutron intensity data differs from the exponential relationship that Kodama et al. (1979) found and employed for estimating SWE from moderated neutron intensity. An exponential curve was fit to the 2013/14 and 2014/15 data, but the r^2 was not improved drastically compared to the linear regression, thus linear regression was used for modeling SWE from moderated neutrons. The error bars in Figure 3 and 4, representing standard deviation of manually measured SWE, generally overlap their associated regression line. This indicates that the linear regression captures the variability revealed by the manual snow surveys.

Approximate location of Figure 3 and 4.

3.3 Estimating SWE from moderated neutron intensity above snowpack

The CRP estimated SWE from moderated neutron intensity measurements for both 2013/14 and 2014/15 winters are shown in Figure 5. The 2013/14 regression equation was used to estimate SWE based on the moderated neutron intensity in the form of:

$$SWE_{CRP} = -0.6044(N_{COR}) + 423.46 \quad (6)$$

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Where SWE_{CRP} is in mm and N_{COR} is the corrected and scaled moderated neutron intensity. A correction for the difference in soil water storage between 2013/14 and 2014/15 was applied when estimating SWE for 2014/15 by subtracting 23.8 mm from the calculated SWE_{CRP}.

For both winters, the CRP-estimated SWE match the manually measured SWE well. Of course for 2013/14 the manually measured SWE corresponds nicely to the CRP-estimated SWE since the regression equation from 2013/14 was used for SWE prediction. The CRP-estimated SWE for 2014/15 also agrees with manually measured SWE. The root-mean-squared error (RMSE) and mean absolute error for the 2014/15 CRP-estimated SWE is 8.8 and 7.5 mm, respectively. These error results are comparable to Rasmussen et al. (2012), who found an RMSE of 5.1 mm between SWE estimated from snow depth and from a CRP. 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.

Snowpack melt occurred during both winters, brought about by warmer temperatures and consistent solar radiation, with significant melts occurring in February 2014 and January 2015. The CRP-estimated SWE responded to the melt in February 2014 with a noticeable decrease at the end of January and early February (Figure 5). However, the CRP overestimated SWE during the melt period in January 2015 (Figure 5). In January 2015 the manually measured SWE was approximately 20 mm, while the CRP-estimated SWE was generally between 30 and 40 mm. In late January 2015 the CRP-estimated SWE did finally decrease with a corresponding decrease in manually measured SWE. This overestimation of

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SWE by the CRP during snowpack melt periods is likely caused by a significant portion of snowmelt water that is removed from the snowpack and deposited in or above the upper soil profile. 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.

Desilets et al. (2010) also witnessed an overestimation of SWE by the CRP following a snowmelt period. Nearly all of the snowpacks they studied appeared to have melted close to the end of their winter study season followed by a large snowfall event causing a rapid increase in CRP-predicted SWE. Manual measurements of SWE around the CRP location gave a mean of roughly 25 mm, while the CRP-estimated SWE was around 55 mm (Figure 2 in Desilets et al., 2010). This CRP overestimation of SWE could also be attributed to snowmelt water remaining in the top of the soil profile and decreasing the moderated neutron intensity.

Approximate location of Figure 5.

3.4 Comparison of CRP and snow depth estimated SWE

The CRP-estimated SWE was also compared to estimated SWE from snow depth measurements at two different reference sites near the study site. The linear relationship between SWE and snow depth found by Shook and Gray (1994) was used to estimate SWE from point measurements of snow depth at the reference sites. The average SWE and snow depth from the 2013/14 and 2014/15 snow surveys followed the Shook and Gray (1994) relationship quite well (Figure 6). Figure 7 contains the CRP-estimated SWE along with SWE estimated from the SRC and Saskatoon Airport RCS sites. As mentioned earlier, the SRC site is roughly 2 km away from the study site and the Saskatoon Airport RCS site is approximately 8 km away. The reference sites are similar to the study site in the way that all three are open

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areas containing little to no trees. The SRC site, located in the middle of an agricultural field (located within the city of Saskatoon) and nearest to the study site, is similar to the CRP location in terms of topography and the surrounding area. It is difficult to quantitatively compare the snow depth results to the CRP-estimated SWE since the two measurement sites are located some distance from the CRP and only a single point measurement was made at each of these reference sites. Thus, the snow depth measurements might not be accurate or spatially representative for SWE, but they do allow the examination of the snowpack dynamics in this region.

Looking at Figure 7, 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. At the beginning of each winter SWE appears at very similar times at all three sites. Increases in SWE also appear at comparable times at all sites. The aforementioned melt periods in January and February of each winter appear more noticeable in the SRC and Saskatoon Airport RCS estimates than in the CRP estimates. In February 2014 it can be seen that the SRC-estimated SWE is consistently lower than the CRP-estimated SWE. Higher SWE at the study site could be attributed to increased accumulation of snow along the irrigation line in the center of the CRP study site.

It is also interesting to note the late accumulation of snow near the end of March 2015. All three sites show an increase in SWE from the final snowfall event at the end of the winter in 2015. Despite all three sites being over 2 km away from each other and the strong spatial variability of SWE, the general trend is comparable signifying that the CRP is performing well in terms of estimating SWE.

Approximate location of Figure 6 and 7.

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3.5 Footprint for CRP-estimated SWE

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.

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4. Conclusions

A simple empirical equation for estimating SWE with the use of a cosmic-ray soil moisture probe was presented. It was found that the relationship between above-ground moderated neutron intensity and manually measured field SWE was well represented by a negative linear function. CRP-estimated SWE corresponded well with snow surveys performed inside the CRP's measurement footprint. SWE estimates based on snow depth measurements at two sites near the study site were also in accordance with the CRP-estimated SWE. Overall, the presented equation performed favourable with regard to providing an estimate of average field SWE at this agricultural study site.

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There are several advantages associated with measuring SWE using a CRP. The measurement footprint of the CRP (~300 m radius) is appealing since it provides a measurement scale between that of the point scale (snow tubes, snow pillows) and large scale (remote sensing). The CRP can be installed in remote locations where consistent snow surveys are not possible. It is far less laborious to estimate SWE passively using the CRP than to conduct field-scale snow surveys. Also, the CRP can provide a continuous estimate of SWE throughout the winter season. Furthermore, there are currently numerous CRPs located worldwide, for example the US COSMOS network (Zreda et al., 2012), that currently only collect soil water data, but could collect SWE data at no additional cost.

One apparent limitation with using the CRP to estimate SWE arises from the occurrence of considerable snowmelt during the winter months. Significant snowmelt occurred in both of the studied winter seasons and both situations caused the CRP to overestimate SWE. Hydrogen molecules affect moderated neutron intensity, thus any melted snow is still recognized by the CRP despite not actually representing snow (SWE) in the field.

However, it appears that it requires substantial snowpack melt in order for the CRP to overestimate SWE.

Similar to the way the moderated neutron intensity is affected by snowmelt water, the CRP measurement is also influenced by the soil water storage in the top of the soil profile beneath the snowpack being measured. CRPs may overestimate SWE by measuring water in soil just below the snow cover. However, the overestimation may be advantageous in some cases because soil water in the surface soil is largely similar to SWE, and controls snowmelt infiltration and surface runoff (Niu and Yang, 2006). Knowing the soil water storage in the upper soil profile is important when applying the presented empirical function at other sites. Differences in soil water storage in the top 10 cm of the soil profile between the two winter seasons in this study clearly showed the effect that water near the soil surface has on the CRP measurement. Therefore, it is important to have a measurement or estimate of the soil water storage in the upper soil profile before snowfall accumulation occurs. This measurement of soil water storage could be measured by the CRP if installed and calibrated before snowfall or in-situ soil moisture probes could be used at the soil surface until freezing. Better understanding the depth to which water within the top of the soil profile affects the CRP reading when a snowpack is present should be looked at in future studies. Other future research should focus on assessing the performance of the empirical relationship at other sites similar to this agricultural study site as well as other forested sites with increased vegetation and snowfall interception.

Acknowledgments

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References:

Archer, D., and D. Stewart. 1995. The installation and use of a snow pillow to monitor snow water equivalent. Water Environ. J. 9(3): 221–230.

Desilets, D., and M. Zreda. 2003. Spatial and temporal distribution of secondary cosmic-ray nucleon intensities and applications to in situ cosmogenic dating. Earth Planet. Sci. Lett. 206: 21–42.

Desilets, D., M. Zreda, and T.P.A. Ferré. 2010. Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays. Water Resour. Res. 46(11): 1-7.

Desilets, D., and M. Zreda. 2013. Footprint diameter for a cosmic-ray soil moisture probe: Theory and Monte Carlo simulations. Water Resour. Res. 49(6): 3566–3575.

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Dietz, A.J., C. Kuenzer, U. Gessner, and S. Dech. 2012. Remote sensing of snow – a review of available methods. Int. J. Remote Sens. 33(13): 4094–4134.

Fang, X., and J.W. Pomeroy. 2009. Modelling blowing snow redistribution to prairie wetlands. Hydrol. Process. 23: 2557–2569.

Franz, T.E., M. Zreda, T.P.A. Ferre, R. Rosolem, C. Zweck, S. Stillman, X. Zeng, and W.J. Shuttleworth. 2012a. Measurement depth of the cosmic ray soil moisture probe affected by hydrogen from various sources. Water Resour. Res. 48(8): 1–9.

Franz, T.E., M. Zreda, R. Rosolem, and T.P.A. Ferre. 2012b. Field Validation of a Cosmic-Ray Neutron Sensor Using a Distributed Sensor Network. Vadose Zo. J. 11(4): 1–10.

Gardner, W. 1986. Water content. In *A. Klute (eds), Methods of Soil Analysis: Part 1 – Physical and Mineralogical Methods*. Soil Science Society of America, Inc., Madison, USA, 493-544.

Goodison, B. E. 1978. Accuracy of snow samplers for measuring shallow snowpacks: an update. Proc. 35th Annu. Meet. East. Snow Conf. 36-49.

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Goodison, B E., H.L. Ferguson and G.A. McKay. 1981. Measurement and data analysis. In *D.M. Gray and D.H. Male (eds), Handbook of Snow: Principles, Processes, Management and Use.* Pergamon Press, Toronto, Canada, 191-274.

Goodison, B.E., J.E. Glynn, K.D. Harvey, and J.E. Slater. 1987. Snow Surveying in Canada: A Perspective. Can. Water Resour. J. 12(2): 27–42.

Gray, M., and P.G. Landine. 1988. An energy-budget snowmelt model for the Canadian Prairies. Can. J. Earth Sci. 25: 1292–1303.

Hobbs, P.V. 1974. Ice physics. Oxford University Press. Great Britain, England.

Knoll, G.F. 1989. Radiation detection and measurement. John Wiley & Sons, Inc. New York, USA.

Kodama, M., K. Nakai, S. Kawasaki, and M. Wada. 1979. An application of cosmic-ray neutron measurements to the determination of the snow-water equivalent. J. Hydrol. 41: 85–92.

Köhli, M., M. Schron, M. Zreda, U. Scmidt, P. Dietrich, and S. Zacharias. 2015. Footprint characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons. J. Hydrol. 6(4): 1–19.

Luojus, K., J. Pulliainen, M. Takala, C. Derksen, H. Rott, T. Nagler, R. Solberg, A. Wiesmann, S. Metsamaki, E. Malnes, and B. Bojkov. 2010. Investigating the feasibility of the

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globsnow snow water equivalent data for climate research purposes. Geosci. Remote Sens. Symp. (IGARSS), 2010 IEEE Int. 19: 4851–4853.

Niu, G.-Y., and Z.-L. Yang. 2006. Effects of frozen soil on snowmelt runoff and soil water storage at a continental scale. J. Hydrometeorol. 7: 937–953.

Paquet, E., M. Laval, L.M. Basalaev, A. Belov, E. Eroshenko, V. Kartyshov, A. Struminsky, and V. Yanke. 2008. An application of cosmic-ray neutron measurements to the determination of the snow-water equivalent. Proc. 30th Int. Cosm. Ray Conf. 1: 761–764.

Pomeroy, J.W. and D.M. Gray. 1995. Snowcover: Accumulation, relocation and management. NHRI Science Report No. 7.

Pomeroy, J. W. and B. E. Goodison. 1997. Winter and snow. *In W. G. Bailey, T. R. Oke, and W. R. Rouse eds. The surface climates of Canada.* McGill-Queen's University Press, Montreal, Can. 68-100.

Rasmussen, R., B. Baker, J. Kochendorfer, T. Meyers, S. Landolt, A.P. Fischer, J. Black, J.M. Thériault, P. Kucera, D. Gochis, C. Smith, R. Nitu, M. Hall, K. Ikeda, and E. Gutmann. 2012. How Well Are We Measuring Snow: The NOAA/FAA/NCAR Winter Precipitation Test Bed. Bull. Am. Meteorol. Soc. 93(6): 811–829.

Rivera Villarreyes, C.A., G. Baroni, and S.E. Oswald. 2011. Integral quantification of seasonal soil moisture changes in farmland by cosmic-ray neutrons. Hydrol. Earth Syst. Sci. 15(12): 3843–3859.

Rosolem, R., W.J. Shuttleworth, M. Zreda, T.E. Franz, X. Zeng, and S.A. Kurc. 2013. The effect of atmospheric water vapor on neutron count in the cosmic-ray soil moisture observing system. J. Hydrometeorol. 14(5): 1659–167.

Shook, K. and D. M. Gray. 1994. Determining the snow water equivalent of shallow prairie snowcovers. In *Proceedings of the 51st Eastern Snow Conference*.

Shook, K., and D. Gray. 1996. Small-scale spatial structure of shallow snowcovers. Hydrol. Process. 10: 1283–1292.

Zreda, M., D. Desilets, T.P. A. Ferré, and R.L. Scott. 2008. Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons. Geophys. Res. Lett. 35(21): 1–5.

Zreda, M., W. Shuttleworth, X. Zeng, C. Zweck, D. Desilets, T. Franz, and R. Rosolem. 2012. COSMOS: The COsmic-ray Soil Moisture Observing System. Hydrol. Earth Syst. Sci. 16(11): 4079–4099.

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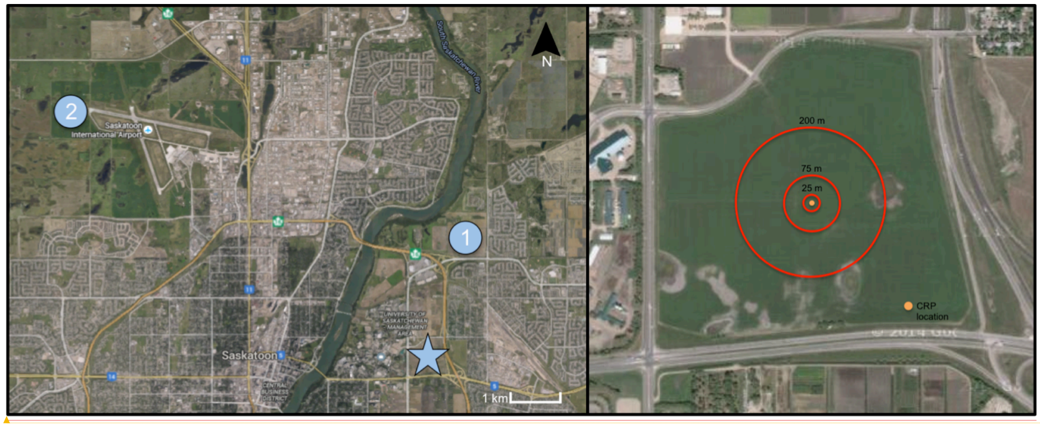

Figure 1. (left) Location of main study site (star), SRC reference site (1), and Saskatoon Airport RCS reference site (2) in Saskatoon SK, Canada. (right) Location of the CRP (orange dot) at the agriculture study site and the 25, 75, and 200 m SWE sampling radials (red lines). Image from Google Maps.

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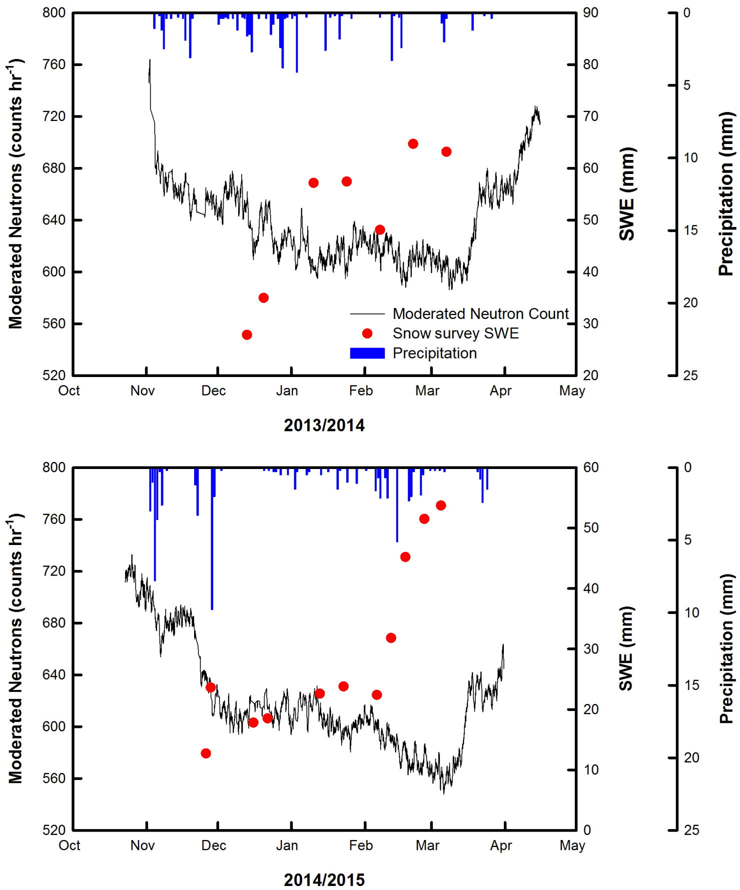

Figure 2. Moderated neutron intensity and snow survey SWE for 2013/14 (top) and 2014/15 (bottom). Precipitation sourced from SRC site and represents daily precipitation.

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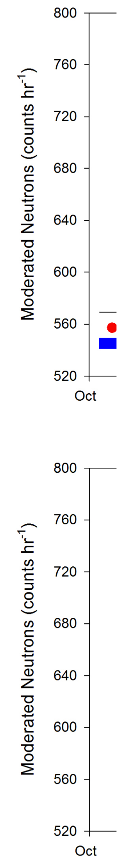

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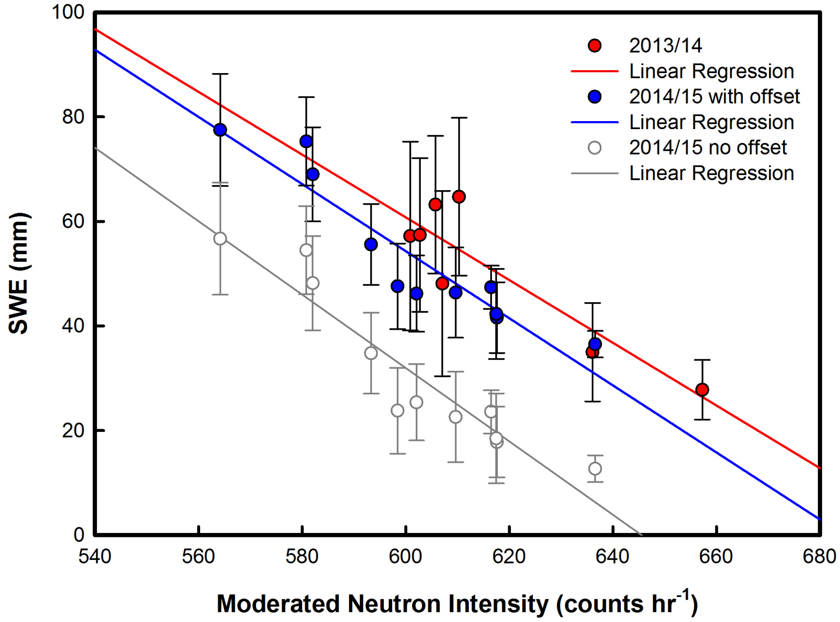

Figure 3. Linear regression of 2013/14, 2014/15 with the soil water storage offset (blue), and 2014/15 with no offset (grey). The red line is the linear regression for 2013/14. The blue and grey lines represent the linear regressions for the 2014/15 data with and without the soil water storage offset, respectively. Error bars represent standard deviation of SWE.

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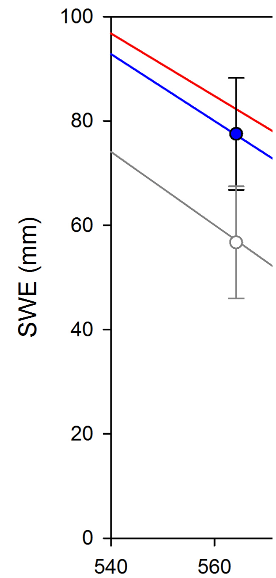

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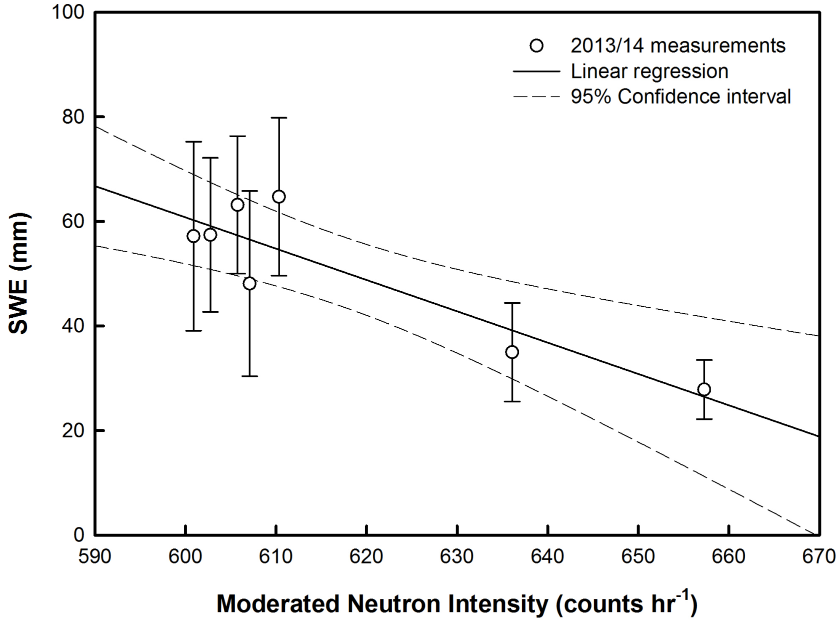

Figure 4. Linear regression of 2013/14 measured SWE and corresponding moderated neutron intensity. Error bars represent standard deviation of SWE.

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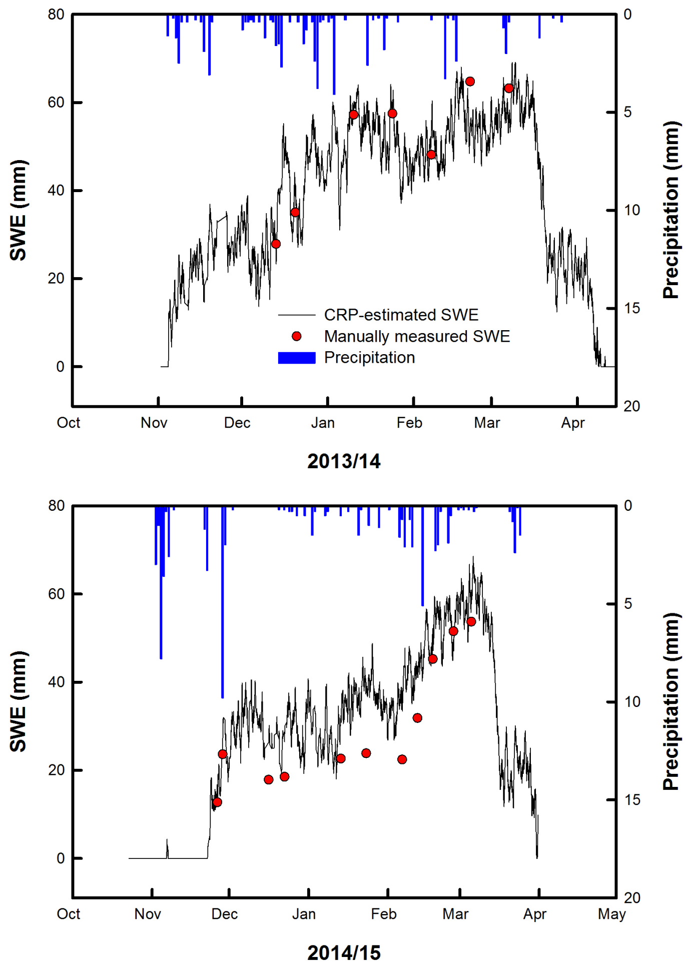

Figure 5. 2013/14 (top) and 2014/15 (bottom) CRP-estimated SWE and manually measured SWE.

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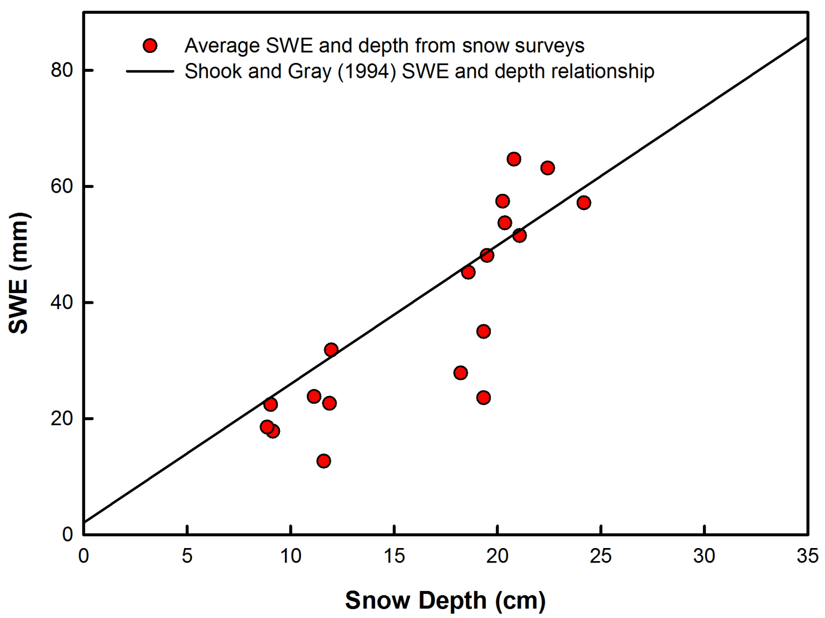

Figure 6. The average SWE and snow depth from the 2013/14 and 2014/15 snow surveys at the CRP study site. The black line represents the linear relationship between SWE and snow depth found by Shook and Gray (1994) for shallow (< 60 cm) snowpacks in the Canadian Prairies.

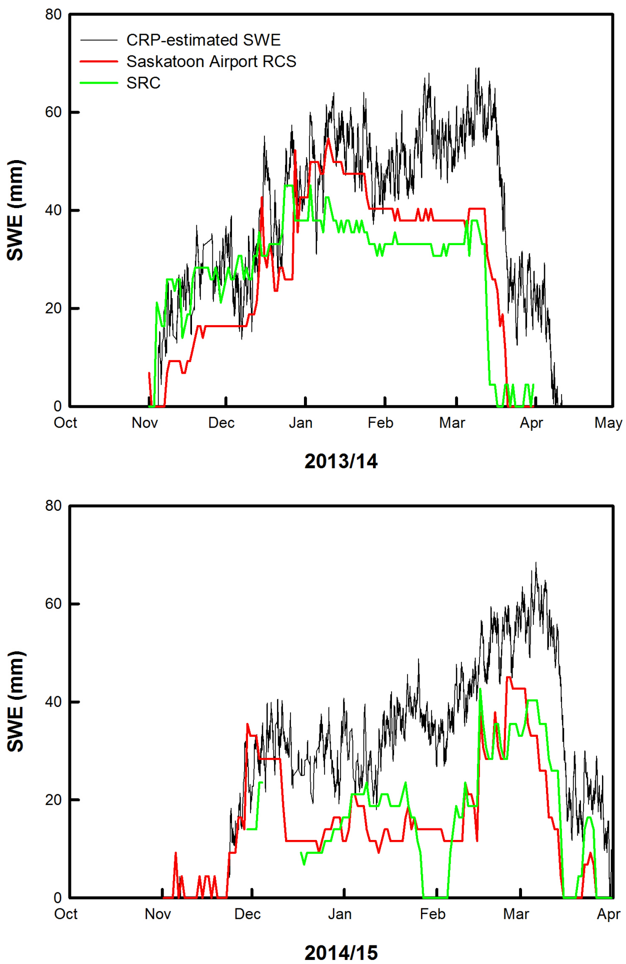

Figure 7. 2013/14 (left) and 2014/15 (right) CRP-estimated SWE and SWE estimated from snow depth.

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