Replies to review comments

MS No.: hess-2016-226

by Andreasen et al.

Referee #1:

The authors present an interesting study combining novel cosmic-ray neutron probe observations with MCNP modeling. The paper is well written and suitable for HESS. Moreover, the paper is a first attempt to better resolve the discrepancies between observed moderated and bare neutron counts and what is modeled with neutron transport simulations. The ability for the CRNP to detect smaller pools of hydrogen in the environment remains a challenging and exciting problem in this field. I have a few suggestions to help improve the manuscript.

Comments:

The Andreasen 2016 WRR article (i.e. pg. 7 L 18 and elsewhere) is not yet available to my knowledge. I suggest the authors remove the citations or include the manuscript for the reviewers to investigate. Hopefully the WRR paper comes out before this paper, otherwise the reference is inappropriate in its current form or without the accompanying manuscript.

AC1 (Author comment # 1): The paper was accepted on July 29 2016. The reference provided in the manuscript has been updated.

Andreasen, M., K. H. Jensen, M. Zreda, D. Desilets, H. Bogena, and M. C. Looms (2016), Modeling cosmic ray neutron field measurements, Water Resour. Res., 52, doi: 10.1002/2015WR018236.

Based off my own unpublished observations of biomass detection with CRNP, I am curious if plotting moderated counts (corrected for water vapor) vs. bare to moderated ratio vs. standing biomass/water equivalence reveals a linear plane. This linear plane is very evident in soybean and maize data. Perhaps plotting the data in this manner will elucidate the biomass and or canopy interception signal?

AC2: We did the plot as suggested by Referee #1. We found a plane, yet, it was not very evident, and we have therefore chosen not to include it in the manuscript.

Pg 3. L6. free parameters is relatively high. . .

AC3: The suggested change has been added to the manuscript.

Pg 4. L11. Should coordinates be in decimal degrees instead of minutes and seconds? Not sure of HESS guidelines. . .

AC4: HESS manuscript preparation guideline for authors has few details on coordinate systems. I have looked through a few papers published by HESS, and here they used the same coordinate system as we do (e.g. Hengl, T., Heuvelink, G. B. M. and van Loon, E. E. (2010): On the uncertainty of stream networks derived from elevation data: the error propagation approach, Hydrol. Earth Syst. Sci., 14, 1153–1165, 2010, doi: 10.5194/hess-14-1153-2010).

Pg 4. L23. How dynamic is the 45% vegetation water component over the year? Were repeated bole gravimetric water measurements made? This turned out to be very important in a study in ponderosa pine in AZ. Unfortunately, tree water content is very rarely reported (i.e. Jenkins 2003).

AC5: Unfortunately, no bole gravimetric measurements were conducted. The same water content is assumed for the whole bole although the water content in the outer rim of a spruce holds more water than in the core of the bole (www.trae.dk - Danish reference). We found this assumption to be appropriate as a first attempt to model the neutron transport for a forest field site, however, we may for future studies include a more detailed description of the trees and the forest canopy.

Pg 7. L 30. Despite the CRNP detector footprint mismatch and volume changes, techniques like eddy covariance have overcame these shortcomings to be established as the gold standard in surface energy balance. This is useful to remember when getting caught up into footprint details that may never be fully resolved. No action items but more of a comment.

AC6: We agree with referee #1 and have changed the wording in Section "Footprint" a bit. A line has been erased: "The potential mismatch in the footprint of the bare and the moderated detectors is a concern when combining the neutron intensity measurements."

The last part of the section is now as follow:

"…The potential mismatch in the footprint of the bare and the moderated detectors is a concern when combining the neutron intensity measurements. Nevertheless, the environmental conditions at the field sites are fairly homogeneous and although the footprint might be different as a first approximation we assume the neutron intensity measured using the bare and the moderated detector are comparable."

Pg 9. L 31. Any idea about the effect of clustering or aggregation of trees in space? Probably beyond the scope of this paper but would be interesting to extend this sensitivity analysis to where the detector is located vs. the local aggregation of tree clustering.

AC7: We have not yet tested the impact of clustering/aggregating the trees, but we would like to in the near future. We have included this in the discussion in section 3.1.:

"Improved comparability to measurements may be obtained by advancing the forest canopy conceptualization. Currently, one tree is defined and repeated throughout the model domain. The trees are placed in even rows and the same settings are applied from the ground surface to 25 m height. In order to advance the forest canopy conceptualization, trees of different heights and diameters could be included, and the placement of the trees could be more according to the actual placement of trees at the forest field site. Additionally, variability in tree trunk diameter, foliage density and volume with height above the ground surface could be implemented."

Pg 11. L 29. The relative uncertainty for hourly time series is lower than 2-12 hr and daily? Is that true?

AC8: Thanks for pointing this out. "Lower" has been changed to "higher".

Pg 12. L1. Very different despite of similar soil? Sentence doesn't make sense, please revise.

AC9: The paragraph has been changed:

"Still, some differences are observed between the neutron height profiles measured in November 2013 and March 2014. The soil moisture was similar during the time of neutron profile detection and we expected the differences to be …"

Pg 15. L9. As we from the calculation? Sentence doesn't make sense, please revise.

AC10: The sentence has been changed: "We choose not to include measurements in the figure because the measurement uncertainty at a relevant integration time is greater than the signal of canopy interception."

Pg. 16 L 30. Are highly variable. . .

AC11: The suggested change has been added to the manuscript.

Pg 18. L 7. A remarkable fit. . .

AC12: The suggested change has been added to the manuscript.

Referee #2:

The Authors present the results of a neutron model used to explore the effect of different hydrogen pools on the signal of the Cosmic-Ray neutron sensors (CRNS). The neutron model was set-up to mimic a specific forest site in Denmark. Based on that, a sensitivity analysis (SA) to several environmental conditions (7 factors) was provided. The effect on thermal neutrons, epithermal neutrons and sensors placed at different heights are discussed. The study is relevant since the CRNS is a method that was applied in several conditions for soil moisture measurements but the role of other hydrogen pools has to be further investigated. Overall, the manuscript (MS) could be an interesting publication suitable for HESS. However, it needs improvement in different directions. The story line is not always consistent, the introduction part is limited and the presentation of the results should be better organized. Finally, I think the MS could be extended with a discussion section. For these reasons I think the Authors should put some more effort to improve the manuscript before publication.

AC13: We agree that the story line is a bit week and that the paper is a bit hard to read. We find your comments and suggestions very helpful. The introduction and results section has been changed considerably, and the conclusion has been updated and improved.

Details on our edits and changes are provided in the sections below.

General comments

[1] The story line is built on the use of CRNS for biomass and canopy interception while a SA is conducted to explore the role of several other hydrogen pools. Moreover, in my opinion, the manuscript is relevant also because the neutron modeling explores in details the use of thermal neutrons and, for the first time, the use of sensors placed at different heights. However, these two novel aspects are completely missed in the introduction and they are taken for granted in the discussion of the results. For these reasons I think the story line is not consistent with the actual analysis reported and introduction and conclusions does not provide a clear roadmap and summary of what this study accomplishes. Overall the manuscript should be reshaped along a clearer story line more consistent with the analyses reported where the Readers should be introduced to the actual state of the CRNS applications (e.g., only moderated counter and just above ground measurements). Novelties of the study and concluding remarks about potentiality and limitations should be better clarified in the final conclusions (i.e., the use of the bare counter and ratio between bare and moderated; the use of sensors placed at different heights; the effect of several environmental conditions to the signal). Specific comments/suggestions are reported below.

AC14: As suggested by the reviewer we have reworked the manuscript to obtain a clearer story line.

The introduction has been reworked:

"The ability to separate the signals of the different hydrogen pools on the neutron intensity is valuable both for the advancement of the cosmic-ray neutron soil moisture estimation method and for the potential of additional applications. The potential of determining canopy interception and biomass from the cosmic-ray neutron intensity is valuable as they form essential hydrological and ecological variables. Both are difficult and expensive to measure continuously at larger scales. Although the effect of biomass and biomass growth on cosmic-ray neutron intensity can be accounted for using independent methods, there is currently no established method for independently constraining biomass based on cosmic-ray neutron data alone."

and

"Previous studies examining the effect of hydrogen on cosmic-ray neutron intensity has for most cases considered a single neutron energy range (neutron intensity measured using the moderated neutron detector) at a single height level (typically 1.5 m above the ground). Thermal and epithermal neutrons are both sensitive to hydrogen, but are characterized by very different physical properties resulting in unique responses to environmental settings and conditions at the immediate ground-atmosphere interface. For this reason, thermal and epithermal neutron intensity at multiple height levels above the ground surface are considered in this study.

The study is conducted at a forest field site using thermal and epithermal neutron measurements from bare and moderated detectors constrained with correction factor models (Andreasen et al., 2016) and modeling using the recognized and widely used Monte Carlo N-Particle transport code (MCNP) (Pelowitz, 2013). Neutron transport modeling of specific sites is limited and has only been performed for non-vegetated field sites (Franz et al., 2013b; Andreasen et al., 2016). In this context, forest sites are especially complex to conceptualize as the number of free parameters is relatively high (e.g. biomass, litter, soil chemistry, interception and the structure of the forest). Here, we first focus on modeling a forest field site. The model is developed from measured soil and vegetation parameters at the specific locality. The modeled neutron intensity profiles are evaluated against profile measurements on two different dates separated by five months, and also against time-series of neutron intensity measurements at two heights. Following, the forests environmental impact on thermal and epithermal neutron intensities are identified and quantified by applying a sensitivity analysis based on the model representative of the forest field site. In addition to improving the understanding of the environmental effect on neutron transport the focus is also on examining the potential of detecting intermediate scale canopy interception and biomass from cosmic-ray neutrons. Measurements at an agricultural field site with no biomass and at a heather field site with a smaller amount of biomass are used to underpin the influence of certain environmental variables (e.g., biomass, litter layer). To our knowledge this is the first study which provides a quantitative analysis of the potential of using the cosmic ray technique for estimation of interception and biomass."

The conclusion has been reworked:

"Four forest canopy conceptualizations of increasing complexity were used. Without adjusting parameters and variables, modeled thermal and epithermal neutron intensity profiles compared fairly well with measurements, yet, some deviations from measurements were observed for each of the four forest canopy conceptualization models. The more appropriate forest canopy conceptualization was not obvious from the results as the best fit to thermal neutron measurements was found using complex forest canopy conceptualization, including a tree trunk and multiple materials, while the better fit to epithermal neutron measurements was found using the most simple forest canopy conceptualization, including a homogenous layer of foliage material."…"The sensitivity of canopy interception, dry bulk density of litter and mineral soil, and soil chemistry on neutron intensity was found to be small."

"Neutron intensity was found to be more sensitivity to litter layer, soil moisture and biomass at the forest field site."

"The response to altered amounts of biomass on thermal and epithermal neutron intensity is non-unique for the simple and complex forest conceptualization and further advancement of the forest representation is therefore necessary."

[2] Despite I understand the goal of the Authors to strengthen the need of such a study, I found in the introduction several statements that are misleading (e.g., P2 L19-25). Contrary to what is stated by the Authors, in my knowledge several important contributions were published to address the (wanted or unwanted) effect of additional hydrogen pools. Moreover, most of these studies focused on the effect of

biomass e.g., in addition to the references reported in the MS, preliminary evaluation of biomass were presented in (Rivera Villarreyes et al., 2011); (Franz et al., 2013) presented an approach to isolate any hydrogen pools but soil moisture and showed the estimation of the crop biomass; (Baatz et al., 2015; Hawdon et al., 2014) introduced an empirical correction to account for biomass. In comparison to biomass, the effect of snow on CRNS signal has received much less attentions. Even if the first concepts were already introduced by (Desilets et al., 2010), a preliminary analysis was just presented by (Rivera Villarreyes et al., 2011) and only recently a study with longer time series of snow was published (Sigouin and Si, 2016). Other hydrogen pools were also addressed: e.g., the analysis of the role of little layer was discussed in detail by (Bogena et al., 2013) and in (Baroni and Oswald, 2015) we presented the first measurements for quantifying also the canopy interception. Overall I believe that all these experimental studies called for additional attentions on hydrogen pools than soil moisture. In this context, the present MS is the first modeling study where complex forest is simulated and the effect of several environmental factors are explored. For these reasons I think the MS could represent a good answer to those calls and the introduction of the MS should be rephrased accordingly.

AC15: We agree with the reviewer and we have change the wording as well as included a more detailed description of previous studies examining the effect of other pools of hydrogen than soil moisture on the neutron signal (Section 1.):

"To date, studies have primarily aimed to advance the cosmic-ray neutron soil moisture estimation method by determining correction models to remove the effect of other influencing pools of hydrogen.

Rosolem et al. (2013) examined the effect of atmospheric water vapor on the neutron intensity (10-100 eV; 1 eV = 1.6*10^{-19} J) using neutron transport modeling and determined a scheme to rescale the measured neutron intensity to reference conditions. For the preparation of cosmic-ray neutron data correction for changes in atmospheric water vapor is along with corrections for temporal variations in barometric pressure and incoming cosmic radiation a standard procedure (Zreda et al., 2012).

Most studies have focused on improving the N_0 calibration parameter used for soil moisture estimation at forest field sites but also at high-yielding crop field sites like maize. Bogena et al. (2013) demonstrated the importance of including the litter layer in the calibration for cosmic-ray neutron soil moisture estimation at field locations with a significant litter layer. The N_0 calibration parameter obtained from field measurements was found to decrease with increasing biomass (Rivera Villarreyes et al., 2013; Hornbuckle et al., 2012; Hawdon et al., 2014; Baatz et al., 2015). In order to account for this effect Baatz et al. (2015a) defined a correction model to remove the effect of biomass on the neutron intensity signal. A different approach was presented by Franz et al. (2013b). Here a universal calibration function was proposed where separate estimates of the various hydrogen pools are included for cosmic-ray neutron soil moisture estimation.

Few studies have explored the potential of using the cosmic-ray neutron method for additional applications. Desilets et al. (2010) distinguished snow and rain events using measurements of two neutron energy bands, and Sigouin and Si (2016) reported an inverse relationship between snow water equivalent and the neutron intensity measured using the moderated detector. Franz et al. (2013a) demonstrated an approach to isolate the effect of vegetation on the neutron intensity signal and estimate area average biomass water equivalent in agreement with independent measurements. Finally, the signals of biomass and canopy interception on neutron intensity, measured using the moderated detector, have also been investigated by Baroni and Oswald (2015). They account the higher soil moisture estimated using the cosmic-ray neutron method compared to the up-scaled soil moisture measured at point-scale to be the impact of canopy interception and biomass. The two pools of hydrogen were then separated in accordance to their dynamics."

[3] I found the presentation of the results obtained with the reference model and the forest conceptualizations not clear (P11L24- P13L7). The Authors first stated about a remarkable agreement of the reference model (P12L12). Later they compared different forest conceptualizations and they found the best fit not to be unique (P13L2-4). Similarly they stated that they cannot determine which conceptualization is more realistic (P16l7-9). For this reason they conducted the SA using two conceptualizations. Overall, I believe that the mismatch should be clearly acknowledged from the beginning. Assuming that two forest conceptualizations are selected, the results of the SA could be then presented.

AC16: We agree. The first representation of the results obtained from modeling has been deleted as the same modeling results also are provided in the figure on forest canopy conceptualization. The results are now presented a little differently, the title "The reference" has been changed to "Gludsted Plantation" and the first part of section 3.1. has overall been reshaped. See Section 3.1.

[4] The discussion of the results of the SA is not always clear and together with the 17 images I think the Readers are lost on the major findings of the study. In addition most of the discussion reported is a qualitative description of the figures. I would suggest searching for a way to sum up the results section (i.e., reducing the number of figures) where first the results of thermal and epithermal neutrons are discussed providing a quantitative comparison of the different effect of the environmental conditions explored. Secondly the ratio between thermal and epithermal is introduced and results are discussed for the factors that showed different response in thermal and epithermal neutrons.

AC17: We agree with referee #2. The number of figures has been reduced considerable (from 17 figures to 10 figures). The figures have either been changed and grouped together or erased. Additionally, the description of the measurements and the discussion of the results have been extended.

Changed and erased figures:

Figure 1: The figure have been change and now hold more information.

Figure 3: The results provided in Figure 3 are also provided in Figure 4. Therefore, Figure 3 has been erased.

Figure 7: The figure has been erased, but the modeling results are still provided in Table 5 (now Table 6) and discussed in the manuscript.

Figures 8, 10, 12 and 13: The figures have been lumped into one figure, and the plots have been changed. Now the ground and canopy level thermal and epithermal neutron intensity is provided instead of thermal and epithermal neutron height profiles.

Figures 14 and 15: The figures have been erased because the results were not very promising and the description of the results was tedious. The manuscript now holds a very short description on the difference between ground and canopy level thermal and epithermal neutron intensity. Here, references to Figures 6C (new fig.) and 6D (new fig.), and Table 6 (new table) are included.

New figure: A new figure has been included. The figure sum up the modeling results provided in Figure 16 and 17 and illustrates the relationship between biomass and ground level thermal-to-epithermal neutron ratio using Model Tree trunk, Foliage, Air and Model Foliage, respectively.

Description of measurements (Section 3.1.): "Overall, time-series and profile measurements provide similar results in agreement with theory. The thermal neutron intensity decreases considerable with height above ground surface and is at canopy level reduced by around 50% compared to at the ground level. The epithermal neutron intensity increases slightly with height and is around 10-15% higher at the canopy level compared to the ground level. Still, some differences are observed between the neutron height profiles measured in November 2013 and March 2014. The soil moisture was similar during the time of neutron profile detection and we expected the differences to be a result of different climate and weather conditions related to the seasons of detections (spring and fall)."

Discussion of the results:

Litter layer results (Section 3.3., Figure 6A (new fig.)): "The production rate of low-energy neutrons (<1 MeV) per incident high-energy neutron is higher for interactions with elements of higher atomic mass ($A^{2/3}$, where A is the atomic mass) (Zreda et al., 2012). Heavier elements are in particular found in mineral soil and an increase in the dry bulk density entails a higher production rate and therefore higher neutron intensity. The concentration of hydrogen is increased with an increased dry bulk density of litter material resulting in a greater moderation and absorption of neutrons, and as a consequence lower neutron intensities."

Biomass results (Section 3.5., Figures 6C and 6D (new figs.)): "The neutron intensity depends on how many neutrons are produced, down-scattered to lower energies and absorbed. Including biomass to a system increases the concentration of hydrogen and leads to reduced neutron intensity as the moderation and absorption is intensified. Despite this, increased thermal neutron intensity is provided with greater amounts of forest biomass. We hypothesize that forest biomass enhances the rate of moderation more than the rate of absorption. Thus higher thermal neutron intensity is obtained as the number of thermal neutrons generated by the moderation of epithermal neutrons exceeds the number of thermal neutrons absorbed. This behavior may be due to the large volume of air within the forest canopy. The probability of thermal neutrons to interact with elements within this space is low as the density of air is low."… "The epithermal neutrons produced in the ground escape to the air and are moderated by the biomass, resulting in reduced epithermal neutron intensity with greater amounts of biomass. All models provide in accordance to theory increasing epithermal neutron intensity with height, yet, the reduced steepness of the neutron height profiles with added biomass is unexplained. Oppositely to Model *Tree trunk, Foliage, Air*, the ground level thermal neutron intensity decreases with added biomass. This may be due to the elemental concentration. Here, no space is occupied by a material of very low elemental density and may lead to an increased absorption of thermal neutrons."

[5] It would be interesting to extend the MS with a discussion section where the overall results of the SA are summarized e.g., the advantages of using sensors at different heights, the advantages of using thermal and epithermal neutrons, the misfits of model and measurements and indication for further improvements. Concluding remarks could stress the potential use of CRNS for other applications but it would be interesting to extend the discussion also on the role of the spatial sensitivity of the sensor i.e., any estimation by CRNS is a spatial weighted value of the actual target (e.g., biomass).

AC18: Since the manuscript has been shortened considerably (both in terms of text and number of figures) we have chosen to keep a combined section of results and discussion. The discussion of the results has been extended (see AC17), and we believe that we have addressed the potential of using the difference between ground and canopy level neutron intensity and t/e ratio. Furthermore, suggestions on how to improve the comparability of measurements and modeling are also provided in this section. We hope that the section has been structured more adequately, and that the outcome of the study is clearer for the reader.

Finally, it is stated that for a good matching between measurements and simulations it was important the correcting factor (Page 7, L10-23). Since all the probes installed so far around the world does not account for that, it would be important to know what the implications are e.g., could we aspect the same sensitivity to environmental conditions when comparing bare and moderated counter instead of thermal and epithermal neutrons?

AC19: Thermal and epithermal neutrons are both sensitive to hydrogen but are also characterized by very different physical properties. We expect unique responses to environmental settings, and pure thermal and epithermal neutron signals are therefore important examining the effect of environmental impact on neutron transport. This is already stated in the introduction, yet, to emphasize the importance of pure thermal and epithermal neutron signals an additional line has been added to Section 2.2.2.:

"We expect thermal and epithermal neutrons to have unique responses to environmental properties and settings. Therefore, it is important to consider pure signals of thermal and epithermal neutrons, and not simply the raw neutron intensity signal measured by the bare and moderated detectors."

Specific comments

Page 1, L1-2: the title's focus on biomass and canopy interception is not entirely representative of the sensitivity analysis presented in the MS, which is broader. It should be rephrased accordingly.

AC20: The title has been changed:

"Cosmic-ray neutron transport at a forest field site: identifying the signature of biomass and canopy interception."

Page 1, L18: in my knowledge the effect of snow has received much less attention than other hydrogen pools. In addition, the analysis reported in the MS does not focus on biomass and interception but several other factors are discussed. For this reason I would rephrase the sentence in ". . .soil moisture but several other hydrogen pools affect the signal".

AC21: The suggested change has been added to the manuscript.

Page 1, L22-31: in my opinion the presentation of the main results should be extended to honor also the other analyses provided in the MS (i.e., the role of the other factors).

AC22: More results are included in the abstract (underlined text=newly added text):

"A sensitivity analysis is performed to quantify the effect of soil moisture, complexity of soil matrix chemistry, forest litter, soil bulk density, canopy interception and forest biomass on thermal and epithermal neutron intensities at multiple height levels above the ground surface. Overall, modeled thermal and epithermal neutron intensities are in satisfactory agreement with measurements, yet, the forest canopy conceptualization is found to be significant for the modeling results. The results show that the effect of canopy interception, soil chemistry and dry bulk density of litter and mineral soil on neutron intensity is small, while the sensitivity to litter layer thickness and biomass in addition to soil moisture is found to be significant. The neutron intensity decreases with added litter layer thickness, especially for epithermal neutron energies. Forest biomass has a significant influence on the neutron intensity height profiles at the examined field site, altering both the shape of the profiles and the ground level thermal-to-epithermal neutron ratio."

Page 2, L12: the terminology used (static, quasi-static and dynamic) is too arbitrary. For a clearer discussion I would suggest presenting the hydrogen compartments in term of temporal scales (e.g., hours/days, season, years).

AC23: We choose this terminology because this is used for papers within the same field of research (see Franz et al., 2013 and Bogena et al., 2013).

Page 2, L15: for consistency I would mention here that the signal of hydrogen pools with low temporal dynamic (e.g., lattice water, SOC etc) is usually subtracted.

AC24: The work done by Franz et al., (2013) has been included in the introduction. They determined a universal calibration function for soil moisture estimation. The effect of other pools of hydrogen on the neutron intensity is included and the practice of subtracting the effect of lattice water and soil organic carbon origins from this work. We are not dealing with soil moisture estimation and we are for that reason not stating the approach directly as suggested by the reviewer.

Page 2, L18-25: see general comment #2 and the additional references reported to reshape the paragraph.

AC25: See AC15

Page 2, L26 – Page 3, L18: the sensitivity analysis focuses on several environmental conditions. In the light of reshaping the MS to honor this, I would say that these paragraphs are not relevant and could be omitted.

AC26: The focus on the environmental signature on the neutron transport has been amplified, yet, we chose to hold on to a special focus on canopy interception and biomass because these in particular are interesting as they form essential hydrological and ecological variables. Thus, we have not omitted the paragraphs.

Page 3, L19 – L34: summary of the aims of the paper and the methods should be rephrased to honor the actual analysis i.e., sensitivity analysis to environmental conditions to understand the role of different hydrogen pools.

AC27: The summary of the aims of the paper has been reshaped:

"Previous studies examining the effect of hydrogen on cosmic-ray neutron intensity has for most cases considered a single neutron energy range (neutron intensity measured using the moderated neutron detector) at a single height level (typically 1.5 m above the ground). Thermal and epithermal neutrons are both sensitive to hydrogen, but are characterized by very different physical properties resulting in unique responses to environmental settings and conditions at the immediate ground-atmosphere interface. For this reason, thermal and epithermal neutron intensity at multiple height levels above the ground surface are considered in this study.

The study is conducted at a forest field site using thermal and epithermal neutron measurements from bare and moderated detectors constrained with correction factor models (Andreasen et al., 2016) and modeling using the recognized and widely used Monte Carlo N-Particle transport code (MCNP) (Pelowitz, 2013). Neutron transport modeling of specific sites is limited and has only been performed for non-vegetated field sites (Franz et al., 2013b; Andreasen et al., 2016). In this context, forest sites are especially complex to conceptualize as the number of free parameters is relatively high (e.g. biomass, litter, soil chemistry, interception and the structure of the forest). Here, we first focus on modeling a forest field site. The model is developed from measured soil and vegetation parameters at the specific locality. The modeled neutron intensity profiles are evaluated against profile measurements on two different dates separated by five months, and also against time-series of neutron intensity measurements at two heights. Following, the forests environmental impact on thermal and epithermal neutron intensities are identified and quantified by applying a sensitivity analysis based on the model representative of the forest field site. In addition to improving the understanding of the environmental effect on neutron transport the focus is also on examining the potential of detecting intermediate scale canopy interception and biomass from cosmic-ray neutrons. Measurements at an agricultural field site with no biomass and at a heather field site with a smaller amount of biomass are used to underpin the influence of certain environmental variables (e.g., biomass, litter layer). To our knowledge this is the first study which provides a quantitative analysis of the potential of using the cosmic ray technique for estimation of interception and biomass."

Page 4, L1-2: the sentence is misleading: as reported in general comment #2 several publications were presented to estimate biomass. In (Baroni and Oswald, 2015) we have also presented the first measurements of canopy interception. Even in the case the Authors have any concerns about these studies, I think it would be part of the constructive advanced of the research field to integrate these opinions in the MS.

AC28: The introduction has been reworked and extended. See AC15.

Page 4, L3: this section 2 could be moved and integrated in the section 3.2.4 Field measurements.

AC29: Thank you for the suggestion. We have integrated section 2 in section 3.2.4.

Page 7, L10-23: for a clearer description of the results, the Authors could start the section making the list of the factors analyzed and referring here also to table 5. In addition the values presented in Table 5 could be plotted for easier comparison (e.g., bar plot).

AC30: Page 7, L10-23 is the section about pure thermal and epithermal neutron detection. Did you mean Page 11 L23?

We list and descried the factors analyzed in section 2.3.2. – the section just before Section 3 ("Results and discussion").

We considered the suggestion on presenting the values of Table 5 (now Table 6) in a different way. However, neither bar plots or other figure plots improved the presentation of the results. In addition, the table values are for most cases a supplement to figure presentations of the modeling results. Thus, we chose not to change the way we presented the values given in Table 5 (now Table 6).

Page 12, L4: I'm surprised: do you really think that the soil moisture profiles could explain such a difference? But in case it is relevant, why did you not evaluate this in the SA? Overall understanding the role of the different factors (i.e., environmental conditions) is the goal of the SA and of this paper.

AC31: We would like to test many more properties and settings, yet, this would make the manuscript tedious and overwhelming. We expect the differences in the neutron intensity profiles measured in November 2013 and March 2014 to be a result of different soil moisture profiles, different climate and weather conditions related to the seasons of detections (spring and fall) and measurement uncertainty. A sentence describing this is included in section 3.1.

Page 12, L12: I think the term "remarkable agreement" should be rephrased in the light of the overall discussion reported about the discrepancies and the inability to define which conceptualization is more realistic (e.g., P16L8). In addition I noticed that the thermal measurements show a regular decreasing from the ground to the canopy level. On the contrary the epithermal measurements show an inversion: the measurements decrease from ground to 5 meters and then start to increase regularly when moving to the canopy level. If I'm not wrong none of the models conceptualizations and the different environmental settings is able to reproduce this behavior. For this reason I think it could be an important result to discuss. Unfortunately this behavior is detected only for the profile measured on Mar-2014 while the measurements conducted on Nov- 2013 does not have these measurements in the plot: is this a mistake in plotting or really do you not have these measurements?

AC32: The decreasing epithermal neutron intensity from ground level to 5 m above the ground surface followed by increasing neutron intensities is expected to be a result of measurement uncertainties. In the beginning of Section 3.1 we describe how we rely more on time-series measurements and we discuss why the two neutron height profiles (November, 2013 and March, 2014) are different despite of similar soil moisture. We have added a few lines (Section 3.1.) on the overall behavior of the measured time-series and profiles of thermal and epithermal neutrons:

"Overall, time-series and profile measurements provide similar results in agreement with theory. The thermal neutron intensity decreases considerable with height above ground surface and is at canopy level reduced by around 50% compared to at the ground level. The epithermal neutron intensity increases slightly with height and is around 10-15% higher at the canopy level compared to the ground level."

Page 12, L26: if it is a SA the results should be discussed in term of sensitive or not sensitive. The term "satisfactorily" suggests that here you are still looking for a forest conceptualization that fits the profile measurements. See also general comment #3.

AC33: "modeled satisfactorily" has been changed to "in agreement with measurements".

Page 13, L8-19: this paragraph could be titled as a new section e.g., effect of soil moisture. Possibly, the analysis could be extended to explore the effect of soil moisture profiles (see also comment Page 12, L4).

AC34: Thank you for the suggestion. Section "Soil moisture" has been added.

Page 14, L25 - Page 15, L8: the presentation of the results jumps from the description of the thermal neutrons to the ratio i.e., epithermal neutrons are not described. For a clearer presentation I would suggest first to discuss both thermal and epithermal neutrons. Secondly, to introduce the use of the ratio explaining the reasons for doing that e.g., what do you expect to see with the use of the ratio instead of the single signal?

AC35: We have extended the description in Section "Canopy interception" a little (underlined text=newly added text):

"Except for a slight increase in ground level thermal neutron intensities with wetting of the forest canopy, no effect of canopy interception on <u>ground and canopy level thermal and epithermal</u> neutron intensity is observed."

Page 18, L21 - Page 19, L5: the discussion about the results obtained with the field locations of Voulund and Harrild is very limited and it refers to analysis presented in the submitted (and not available) paper of Anderson et al. (2016). Moreover I think that at the current status, these results do not provide any new insights on the present study. Either the Authors integrate better the description, the analyses and the results obtained in these locations, or in my opinion the results obtained based on these two sites could be completely omitted in this MS.

AC36: Andreasen et al. (2016) has since the submission of this paper to HESS been accepted (the reference is given in AC1). In our opinion the measurements of Voulund Farmland and Harrild Heathland is valuable for the manuscript. They confirm that litter and biomass increases the ground-level thermal-to-epithermal neutron ratio, and that the modeled values agree with measurements.

Page 18, L19: as discussed also in previous comments. I think the term "remarkable agreement" is misleading. On the contrary I think the misfits are interesting results to highlights providing the base for further studies.

AC37 (Page 19, L19): We have reworked the conclusion and changed the wording ("remarkable agreement" is out). See AC14.

Page 18, L22: before starting speaking about canopy interception, I would introduce also a summary of the role of the other hydrogen pools explored. This would better honor the SA reported in the MS.

AC38: We have added the results of the sensitivity analysis to the conclusion. See AC14.

Technical corrections

Page 4, L11: eV

AC39: The typo has been corrected (Section "Terminology").

Page 13, L26: the definition (4th order, 3rd order) of the chemical complexity are not self-explained. I would suggest instead the use in the table of other definitions e.g., (SOM+Gd+Root+??+SiO2) for the more complex and so on.

AC40: We choose to keep the current terminology (4th order, 3rd order…), however, we have both edited the wording in Section 3.3. and the table caption.

Section 3.3.: "Soil organic matter, below-ground biomass, Gd and the chemical composition from XRF measurements are excluded one at the time (from *third* to *first order complexity*) and the final model includes a simple silica soil (*SiO_2*). The exact sensitivity of excluding the different components on ground and canopy level thermal and epithermal neutron intensity is quantified in Table 6 (see values in parentheses). Only the removal of soil organic matter (*third order complexity*) changes the neutron intensity significantly at Gludsted Plantation …"

Table 6 caption: "… Values provided in parentheses specifies the direct effect of one-by-one excluding soil organic matter (*third order complexity*), Gd (*second order complexity*), below ground biomass (*first order complexity*) and site specific major elements soil chemistry (SiO_2)."

Page 13, L28: what is cts? To be defined.

AC41: Cts is counts. This has been specified in text (Section 3.3.).

Page 15, L4: conditions instead of locations.

AC42: The suggested change has been added to the manuscript.

Figure 1: the domain represented in the figure is too extended and not well informative. I would suggest using this as a general overview but adding also a panel where the positions of the experimental sites are visualized with higher resolutions.

AC43: Figure 1 has been change, and now includes more information.

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Referee #3:

General Comments:

In this paper the authors use a model to investigate how different model conceptualizations and different model parameters influence both thermal and epithermal neutron intensities from the ground surface up to a height of 35 m. They want to find out whether it is possible to use combined measurements of thermal and epithermal neutrons at ground level to determine both aboveground vegetation biomass (quasi-statically) and canopy interception (dynamically). In order to do that they need to assess whether there are factors other than aboveground biomass and interception that alter the ratio of thermal to epithermal neutron intensity. I like the approach. It is novel to measure neutron intensities at different heights in a forest and it is novel to try to use the ratio of thermal to epithermal neutrons for biomass determination. Therefore the topic is interesting and the paper is well-suited for publication in HESS.

Still, there is room for improvement. In the end as a reader I felt a little lost on what are the actual outcomes from the study. It seems as if equifinality is a very big problem. Many of the investigated model setups and parameters seem to influence the detected neutron intensity profiles and therefore it is unclear which setup represents reality best. Unfortunately, the discussion section often lacks more detailed interpretations of the comparison of model results and measurements. Therefore the full potential of the study is not yet explored.

So my main point is that a refocus of the discussion section (away from just describing towards interpreting) would definitely improve the manuscript and the value for the reader.

AC44: Thank you for your comments and suggestions. We agree that the manuscript is a bit tedious and that the discussion of the results could be improved. We have revised the manuscript in order to ease the readability and clarify the focus.

Specific Comments:

p. 1, l. 1: Title: Since canopy interception only plays a minor role in the paper, I would suggest removing it from the title. You are investigating so many more things, like forest canopy representation, complexity of soil matrix chemistry, litter, soil bulk density. A more obvious choice for the title might be going along the line of forest canopy representation (since this part appears most prominently and novel when reading the manuscript). Also, posing a question in the title is not ideal, especially when you answer one part of it with no and the other part with yes.

AC45: We have changed the title to:

"Cosmic-ray neutron transport at a forest field site: identifying the signature of biomass and canopy interception."

p. 1, l. 31: It would be good to insert an explicit concluding statement into the abstract that answers the question you were posing in the title. ('Therefore we conclude that while there is potential to infer biomass from cosmic… canopy interception cannot be inferred.')

AC46: The title has been changed and is no more containing a question. Still, concluding statement on the potential of quantifying canopy interception and biomass using cosmic ray neutron detection is relevant and a few lines has therefore been added to the abstract (underlined text=newly added text) (see also AC22):

"A sensitivity analysis is performed to quantify the effect of soil moisture, complexity of soil matrix chemistry, forest litter, soil bulk density, canopy interception and forest biomass on <u>thermal and epithermal neutron</u>

intensities at multiple height levels above the ground surface. Overall, modeled thermal and epithermal neutron intensities are in satisfactory agreement with measurements, yet, the forest canopy conceptualization is found to be significant for the modeling results. The results show that the effect of canopy interception, soil chemistry and dry bulk density of litter and mineral soil on neutron intensity is small, while the sensitivity to litter layer thickness and biomass in addition to soil moisture is found to be significant. The neutron intensity decreases with added litter layer thickness, especially for epithermal neutron energies. Forest biomass has a significant influence on the neutron intensity height profiles at the examined field site, altering both the shape of the profiles and the ground level thermal-to-epithermal neutron ratio."

p. 2, l. 2: '..relativeLY high concentration CLOSE TO THE LAND SURFACE,…'

AC47: The suggested change has been added to the manuscript.

p. 2, l. 2-10: I would reorder this paragraph. Start with the role of soil moisture and the difficulties of its detection. Then introduce cosmic-ray neutrons and the detector before mentioning its footprint in line 7.

AC48: We have reordered the section following the suggestions of Referee #3 (see Section 1.).

p. 2, l. 13: In Table 1 you use the word 'transient', here you say 'dynamically'.

AC49: We have change the word "transient" to the word "dynamic" in Table 1.

p. 2, l. 13-14: Try to categorize this list. 'Hydrogen is stored statically in water in soil minerals and buildings/roads, quasi-statically in…'

AC50: The suggested change has been added to the manuscript.

p. 2, l. 31: 'HOWEVER, the spatial scale of measurement…'

AC51: The suggested change has been added to the manuscript.

p. 3, l. 27: '…we PERFORM a sensitivity analysis…'.

AC52: The paragraph has been changed:

"The study is conducted at a forest field site using thermal and epithermal neutron measurements from bare and moderated detectors constrained with correction factor models (Andreasen et al., 2016) and modeling using the recognized and widely used Monte Carlo N-Particle transport code (MCNP) (Pelowitz, 2013). Neutron transport modeling of specific sites is limited and has only been performed for non-vegetated field sites (Franz et al., 2013b; Andreasen et al., 2016). In this context, forest sites are especially complex to conceptualize as the number of free parameters is relatively high (e.g. biomass, litter, soil chemistry, interception and the structure of the forest). Here, we first focus on modeling a forest field site. The model is developed from measured soil and vegetation parameters at the specific locality. The modeled neutron intensity profiles are evaluated against profile measurements on two different dates separated by five months, and also against time-series of neutron intensity measurements at two heights. Following, the forests environmental impact on thermal and epithermal neutron intensities are identified and quantified by applying a sensitivity analysis based on the model representative of the forest field site. In addition to improving the understanding of the environmental effect on neutron transport the focus is also on examining the potential of detecting intermediate scale canopy interception and biomass from cosmic-ray neutrons. Measurements at an agricultural field site with no biomass and at a heather field site with a smaller amount of biomass are used to underpin the influence of certain environmental variables (e.g., biomass, litter layer). To our knowledge this is the first study which provides a quantitative analysis of the potential of using the cosmic ray technique for estimation of interception and biomass."

p. 3, l. 28: Only to look at their effect on MODELED thermal and epithermal neutron intensity? Or also to make statements about their effect on ACTUAL thermal and epithermal neutron intensity?

AC53: The paragraph has been changed. See AC52.

p. 4, l. 16: Could you shortly introduce what this 'root-to-shoot ratio' is?

AC54: We have included an explanation to the sentence (the added text is underlined):

"The dry below-ground biomass was calculated to be 25 t/ha using a root-to-shoot ratio (the weight of the roots to the weight of the aerial part of the plant) for Norway spruce of 0.25 (Levy et al., 2004)."

p. 4, l. 16: Information? Be more specific.

AC55: Some examples of the sort of information provided by The Danish Nature Agency have been included in the sentence (the added text is underlined):

"Information on the vegetation at the forest field site (e.g. tree species, ages, heights and trunk diameters) is acquired from a register managed by The Danish Nature Agency (representative of the 2012 conditions); see Table 2."

p. 5, l. 2: Why random soil samples? A composite sample representing mean soil properties would have been much more representative of the soils within the footprint of the sensor given small-scale variability.

AC56: The field sites are located on an outwash plain from the last glaciation composed of sandy soil. We agree that a composite soil sample representing the mean conditions would have been more appropriate, however, the soil is very homogeneous and we are quite confident that two random soil samples are sufficient. The homogeneity of the soil is evident comparing the results of the XRF analysis on two random soil samples collected in 20-25 cm depth at Harrild Heathland and Gludsted Plantation. The two field sites are separated by approximately 10 km and have very similar soil chemistry (see below). The soil chemistry of Voulund Farmland is not included as it due to farming practices contains a wider range of elements.

	Gldusted Plantation [%]	Harrild Heathland [%]
O	52.78	52.76

Si	44.86	44.71
Al	1.54	1.74
K	0.53	0.56
Ti	0.29	0.23

p. 5, l. 24: What do you mean by: '…is observed VISUALLY…'?

AC57: The line has been reworked (Section 2.2.4.):

"The organic rich litter layer is found to be around 10 cm thick during soil sampling field campaigns at the field site."

p. 5, l. 26: Do you mean that the hardpan-layer hinders percolation to deeper depths?

AC58: Yes. The sentence has been reworked (Section 2.2.4.):

"Due to podsolization a low permeable hardpan-layer hindering percolation to deeper depths is present at around 25-30 cm depth."

p. 6, l. 12: represent might not be the right word here. Maybe 'detect' or 'be sensitive to'?

AC59: "Represent" has been replaced with "is sensitive to" (Section 2.1.).

p. 6, l. 13: What do you want to express when you write: 'Despite this fact…'?

AC60: The sentence has been reworked:

"Here, the term epithermal neutrons will be used for both measured neutrons of energies above 0.5 eV and modeled neutrons of energies 10 – 1000 eV."

p. 7, l. 5: The term 'epithermal' includes 'fast', no? So you don't need to say '…fast and epithermal…'.

AC61: That is true. "Fast" has been erased.

p. 7, l. 7: Why do you believe in this minor effect on your results?

AC62: Yes this should be addressed, and was addressed by Andreasen et al. (2016). Therefore, the reference has been added at the end of the sentence.

Andreasen et al. (2016): "Preliminary modeling results by the authors and R. Rosolem (personal communication, 2015) suggest that water vapor only has a minor effect on the thermal neutron intensity measured near the land surface. This is in agreement with earlier studies of Bethe et al. [1940] and Lockwood and Yingst [1956]. However, water vapor corrections might be required for thermal neutron intensities collected high above the ground surface, and future work should address this issue."

p. 7, l. 19-20: What are these correction factor models, when exactly where they applied and how did the output of these models look compared to the cadmium-difference model?

AC63: The neutron energy correction models are described in Andreasen et al. (2016) (see AC1) and in Section 2.2.2. Additionally, a few sentences have been added to Section 2.2.4 specifying when the neutron energy correction models where applied:

”In order to obtain comparability between measurements and modeling pure thermal and epithermal neutron signals were estimated using neutron energy correction models on measurements from bare and moderated detectors, respectively. The neutron energy correction models were both used on time-series and neutron height profile measurements.”

“In order to obtain pure thermal and epithermal neutron height profiles the neutron energy correction models were applied.”

p. 7, l. 32-34: The fact that the environmental conditions at the field sites are fairly homogeneous is no explanation for your assumption that the neutron intensities measured by the two different detectors can be compared. Please elaborate.

AC64: The paragraph has been reworked:

“The potential mismatch in the footprint of the bare and the moderated detectors is a concern when combining the neutron intensity measurements. Nevertheless, the environmental conditions at the field sites are fairly homogeneous and although the footprint might be different as a first approximation we assume the neutron intensity measured using the bare and the moderated detector are comparable.”

p. 9, l. 5-32: What about the sub-canopy structure of real forests? With a lot of the leaves and branch biomass a couple of meters above the ground and only the trunks with a lot of air in between near the ground surface. Would you expect the same outcome? How could this impact your results? It would be good to discuss this somewhere.

AC65: We have not modeled a forest with vertical variation in material and density, yet, it would be interesting to examine in the future. Here, the neutron transport was found to be sensitive to the conceptualization of the forest and we therefore expect that further advancement will have an effect too. However, we have a hard time predicting the effect on neutron transport specifying the sub-canopy structure of the forest. We have included a few suggestions in Section 3.1 on how to advance the forest conceptualization (see also AC5):

“Improved comparability to measurements may be obtained by advancing the forest canopy conceptualization. Currently, one tree is defined and repeated throughout the model domain. The trees are placed in even rows and the same settings are applied from the ground surface to 25 m height. In order to advance the forest canopy conceptualization, trees of different heights and diameters could be included, and the placement of the trees could be more according to the actual placement of trees at the forest field site. Additionally, variability in tree trunk diameter, foliage density and volume with height above the ground surface could be implemented."

p. 10, l. 20-21: Rephrase. Maybe something like: 'The thermal and epithermal neutron intensity is both a product of hydrogen abundance as well as elemental composition…'.

AC66: The suggested change has been added to the manuscript.

p. 12, l. 30: From here on I will ask the question 'Why?' whenever I would like to see a more detailed discussion of one of your results/observations. Throughout the discussion section there are instances where you observe and describe your results without giving a proper (attempt of) interpretation. For example here you state that '…the neutron intensity profiles of the simpler forest canopy conceptualization… is less steep and is the only model providing an epithermal neutron intensity profile within the daily ranges of the time-series measurements…'. Still there is no explanation on why this could be the case.

AC67: This is a very valid point, and we have sought to explain the effect of alterations in the environmental settings on thermal and epithermal neutron intensity. We do not always have an answer, but have in those cases provided some suggestions/thoughts on the measurements and modeling results.

p. 13, l. 19: Why?

AC68: Unfortunately, we have no explanation to why this is. The different results of the two model-setups could from measurements potentially have clarified which of the two model-setup are more appropriate, however, this was unfortunately not the case as both models provide neutron intensities in fairly good agreement with measurements. We have including this consideration in Section 3.2.:

"Neutron intensity at dry and wet soil conditions is represented by the range of time-series neutron intensity measurements. Overall, the modeled neutron intensities are within the measurement range and the more appropriate model-setup for Gludsted Plantation is not obvious from the modeling results."

p. 14, l. 17: Why?

AC69: An explanation has been added to Section 3.3.:

"The production rate of low-energy neutrons (<1 MeV) per incident high-energy neutron is higher for interactions with elements of higher atomic mass ($A^{2/3}$, where A is the atomic mass) (Zreda et al., 2012). Heavier elements are in particular found in mineral soil and an increase in the dry bulk density entails a higher production rate and therefore higher neutron intensity. The concentration of hydrogen is increased with an increased dry bulk density of litter material resulting in a greater moderation and absorption of neutrons, and as a consequence lower neutron intensities."

p. 14, l. 19: How can the mineral soil act as a producer of epithermal neutrons? Thermal neutrons would have to be accelerated to become epithermal. How does this happen?

AC70: An explanation has been added to Section 3.3. See AC69.

p. 15, l. 7: Move '…from the calculation in the previous section…' to the beginning or the end of the sentence.

AC71: The sentences have been rephrased (Section 3.4.):

"We choose not to include measurements in the figure because the measurement uncertainty at a relevant integration time is greater than the signal of canopy interception."

p. 15, l. 31-32: Why?

AC72: We have added a few sentences to explain the response of thermal and epithermal neutrons to increasing amounts of biomass using Model *Tree trunk, Foliage, Air*:

"The neutron intensity depends on how many neutrons are produced, down-scattered to lower energies and absorbed. Including biomass to a system increases the concentration of hydrogen and leads to reduced neutron intensity as the moderation and absorption is intensified. Despite this, increased thermal neutron intensity is provided with greater amounts of forest biomass. We hypothesize that forest biomass enhances the rate of moderation more than the rate of absorption. Thus higher thermal neutron intensity is obtained as the number of thermal neutrons generated by the moderation of epithermal neutrons exceeds the number of thermal neutrons absorbed. This behavior may be due to the large volume of air within the forest canopy. The probability of thermal neutrons to interact with elements within this space is low as the density of air is low."

p. 16, l. 5-6: Why?

AC73: We have added a few sentences to explain the response of thermal and epithermal neutrons to increasing amounts of biomass using Model *Foliage*:

"The epithermal neutrons produced in the ground escape to the air and are moderated by the biomass, resulting in reduced epithermal neutron intensity with greater amounts of biomass. All models provide in accordance to theory increasing epithermal neutron intensity with height, yet, the reduced steepness of the neutron height profiles with added biomass is unexplained. Oppositely to Model Tree trunk, Foliage, Air, the ground level thermal neutron intensity decreases with added biomass. This may be due to the elemental concentration. Here, no space is occupied by a material of very low elemental density and may lead to an increased absorption of thermal neutrons."

p. 16, l. 26-27: Why?

AC74: In order to focus the paper and improve the readability the section on the difference between ground and canopy level neutron intensity has been reduced considerably, and the sentence on p. 16, l. 26-27 has been erased.

p. 17, l. 7-17: So would you say that this model representation is better than the more complex one? It certainly fits better to your observed data. What does it mean that the average conditions (without separate trunk, foliage, air) perform better? It should be the other way around, no?

AC75: The ground level thermal-to-epithermal neutron ratio was found to be more appropriate and convenient in terms of biomass determination. Thus, in order to focus the paper and improve the readability the attention of the difference between ground and canopy level thermal and epithermal neutron intensity, respectively, has been reduce markedly. The conditions mentioned by Referee #3 are not included in the manuscript anymore.

p. 17, l. 22: Do you maybe mean '…prevailING at the field site.'

AC76: The line has been erased (see AC6).

p. 17, l. 31-32: Why?

AC77: A line has been added to the sentence (see underlined part):

"<u>Drying or wetting of soil change the thermal and epithermal neutron intensity proportionally and the ratios are accordingly</u> found to be independent of changes in the ground level thermal neutron intensity, the ground level epithermal neutron intensity and volumetric soil moisture."

p. 18, l. 7-12: Is that an indication that this more complex model is a more realistic representation of the forest environment? How is this observation compatible with the previous observation that shows the better fit of the less complex model when comparing the differences between ground and canopy level thermal and epithermal neutron intensity?

AC78: The results on the difference between ground and canopy level neutron intensity were ambiguous and most discussion and figures on this has been removed to ease the readability and hopefully making the manuscript less comprehensive. Overall, the Model *Tree trunk, Foliage, Air* seems to perform better. The two-year-average of ground level t/e ratio fits the biomass of 100 t/ha estimated for Gludsted Plantation using lidar, and the range of measurements is overall in agreement with the standard deviation of the estimated biomass. Still, more work needs to be done as neither the Model *Tree trunk, Foliage, Air* and Model *Foliage* are fully in agreement with measurements. In order to do this, we have to look at the three points stated a little later in the same paragraph. We have not added any to answer the question asked by referee #3 in the manuscript as most of the section on the difference between ground and canopy level neutron intensity has been removed.

p. 18, l. 13-20: How would each of these 3 factors influence the modeled ratios?

AC79: Of these three factors only shortcomings in the model setup would affect the modeled ratios. This has been specified in the text:

"A model including a sufficient representation of the field site will provide neutron height profiles and t/e ratios more representative of the real conditions…"

p. 19, l. 3: Should the amount of biomass not be slightly larger for the Heathland site compared to the non-vegetated Gludsted plantation?

AC80: Yes. We have rephrased the paragraph:

"Both field sites have a considerable layer of litter, and the slightly higher t/e ratio relative to the non-vegetated Gludsted Plantation may be due to biomass in the form of grasses, heather plants and bushes present at Harrild Heathland."

p. 19, l. 6: It would be helpful to introduce an abbreviation for the term 'thermal-to-epithermal ratio' somewhere at the beginning (Rt/e) and use it throughout the manuscript.

AC81: Good idea. We have included the abbreviation "t/e" in the manuscript.

Figures & Tables:

Figure 1: Provide a map that zooms in onto your study area with a little more detail and move the current overview map of Denmark into one of the corners of the new map.

AC82: Figure 1 has been changed.

Figure 3-10, 12-13: Remove the line in the legend in front of 'Canopy surface model'. I was looking for it but it is not in the actual figure, is it? Maybe just call it 'Modeled' in comparison to 'Measured'.

AC83: The line in front of 'Canopy surface' was supposed to be dashed, and explains the horizontal dashed lined at 25 m height above the ground surface in the figures. I have edited the three figures providing results on neutron height profiles. Now the lines in the legend of the figures are all dashed.

Technical Corrections:

p. 1, l. 25: 'minor' is no adverb. Maybe use 'insignificantly'.

AC84: The suggested change has been added to the manuscript.

p. 1, l. 27: siteS

AC85: The suggested change has been added to the manuscript.

p. 4, l. 5: '…within THE Skjern River…'.

AC86: The suggested change has been added to the manuscript.

References:

A couple of references are listed but not referenced in the text:

Bogena et al. 2013

AC87: The reference is now included in the text (Section “Introduction”).

Heidbüchel et al. 2016

AC88: The reference has been erased from the reference list.

Rivera Villareyes et al. 2013

AC89: The reference is now included in the text (Section “Introduction”).

Cosmic-ray neutron transport at a forest field site: identifying the signature of biomass and canopy interception

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Keywords

1. Cosmic-ray neutron intensity method
2. Neutron transport modeling
3. Canopy interception
4. Forest biomass

Abstract

Cosmic-ray neutron intensity is inversely correlated to all hydrogen present in the upper decimeters of the subsurface and the first few hectometers of the atmosphere above the ground surface. This method has been used for measuring soil moisture but several other hydrogen pools affect the signal. We use a neutron transport model with various representations of the forest and different parameters describing the subsurface to match measured height profiles and time series of thermal and epithermal neutron intensities at a field site in Denmark. A sensitivity analysis is performed to quantify the effect of soil moisture, complexity of soil matrix chemistry, forest litter, soil bulk density, canopy interception and forest biomass on thermal and epithermal neutron intensities at multiple height levels above the ground surface. Overall, modeled thermal and epithermal neutron intensities are in satisfactory agreement with measurements, yet, the forest canopy conceptualization is found to be significant for the modeling results. The results show that the effect of canopy interception, soil chemistry and dry bulk density of litter and mineral soil on neutron intensity is small, while the sensitivity to litter layer thickness and biomass in addition to soil moisture is found to be significant. The neutron intensity decreases with added litter layer thickness, especially for epithermal neutron energies. Forest biomass has a significant influence on the neutron intensity height profiles at the examined field site, altering both the shape of the profiles and the ground level thermal-to-epithermal neutron ratio. The ratio increases significantly with increasing amounts of biomass and insignificantly with canopy interception. Satisfactory agreement is found between measurements and model estimates of biomass results at the forest site as well as two nearby sites representing agricultural and heathland ecosystems. The measured ground level thermal-to-epithermal neutron ratios of the three sites range from around 0.56 to 0.82. A significantly smaller effect of canopy interception on the ground level thermal-to-epithermal neutron ratio was modeled to range from 0.80 to 0.84 for a forest with a dry and a very wet canopy (4 mm of canopy interception), respectively.

1. Introduction

Soil moisture plays an important role in water and energy exchanges at the ground-atmosphere interface, but is difficult and expensive to measure at the intermediate scale (hectometers). The cosmic-ray method has been developed to circumvent the shortcomings of existing measurement procedures for soil moisture detection at the multi hectare scale (e.g. Zreda et al. (2008) and Franz et al. (2012)). The cosmic-ray neutron intensity (eV range) at the ground surface is a product of the elemental composition and density of the immediate air and soil matrix. Hydrogen is, because of its physical properties and often relatively high concentration close to the land surface, a significant element controlling neutron transport. As a result, neutron intensity is inversely correlated with the hydrogen content of the surrounding hectometers of air and top decimeters of the ground (Zreda et al., 2008). Neutron intensity measurements were found to be suitable for the detection of soil moisture since it often forms the major dynamic pool of hydrogen within the footprint of the detector.

Cosmic-ray neutron intensity detection also has potential for estimating other pools of hydrogen present within the footprint of the neutron detector (Zreda et al., 2008; Desilets et al., 2010). Hydrogen is stored statically in water in soil minerals and buildings/roads, quasi-statically in above and below ground biomass, soil organic matter, snow and lakes/streams, or dynamically in soil water, atmospheric water vapor and canopy intercepted precipitation (see Table 1).

Table 1 is inserted here

To date, studies have primarily aimed to advance the cosmic-ray neutron soil moisture estimation method by determining correction models to remove the effect of other influencing pools of hydrogen.

Rosolem et al. (2013) examined the effect of atmospheric water vapor on the neutron intensity (10-100 eV; 1 eV = $1.6*10^{-19}$ J) using neutron transport modeling and determined a scheme to rescale the measured neutron intensity to reference conditions. For the preparation of cosmic-ray neutron data correction for changes in atmospheric water vapor is along with corrections for temporal variations in barometric pressure and incoming cosmic radiation a standard procedure (Zreda et al., 2012).

Most studies have focused on improving the N_0 calibration parameter used for soil moisture estimation at forest field sites but also at high-yielding crop field sites like maize. Bogena et al. (2013) demonstrated the importance of including the litter layer in the calibration for cosmic-ray neutron soil moisture estimation at field locations with a significant litter layer. The N_0 calibration parameter obtained from field measurements was found to decrease with increasing biomass (Rivera Villarreyes et al., 2013; Hornbuckle et al., 2012; Hawdon et al., 2014; Baatz et al., 2015). In order to account for this effect Baatz et al. (2015a) defined a correction model to remove the effect of biomass on the neutron intensity signal. A different approach was presented by Franz et al. (2013b). Here a universal calibration function was proposed where separate estimates of the various hydrogen pools are included for cosmic-ray neutron soil moisture estimation.

Few studies have explored the potential of using the cosmic-ray neutron method for additional applications. Desilets et al. (2010) distinguished snow and rain events using measurements of two neutron energy bands, and Sigouin and Si (2016) reported an inverse relationship between snow water equivalent and the neutron intensity measured using the moderated detector. Franz et al. (2013a) demonstrated an approach to isolate the effect of vegetation on the neutron intensity signal and estimate area average biomass water equivalent in agreement with independent measurements. Finally, the signals of biomass and canopy interception on neutron intensity, measured using the moderated detector, have also been investigated by Baroni and Oswald (2015). They account the higher soil moisture estimated using the cosmic-ray neutron method compared to the up-scaled soil moisture measured at point-scale to be the impact of canopy interception and biomass. The two pools of hydrogen were then separated in accordance to their dynamics.

The ability to separate the signals of the different hydrogen pools on the neutron intensity is valuable both for the advancement of the cosmic-ray neutron soil moisture estimation method and for the potential of additional applications. The potential of determining canopy interception and biomass from the cosmic-ray neutron intensity is valuable as they form essential hydrological and ecological variables. Both are difficult and expensive to measure continuously at larger scales. Although the effect of biomass and biomass growth on cosmic-ray neutron intensity can be accounted for using independent methods, there is currently no established method for independently constraining biomass based on cosmic-ray neutron data alone.

Canopy interception is for some climatic and environmental settings an important variable to include in water balance studies, as well as in hydrological and climatological modeling. For the forest site studied here the canopy interception loss was found to be 31-34% of the gross precipitation, making it a vital variable to consider (Ringgaard et al., 2014). A common method to estimate canopy interception is by subtracting the precipitation measured at ground level below canopy (throughfall) from precipitation measured above the forest canopy (gross precipitation) using standard precipitation gauges. However, the spatial scale of measurement is small and is not representative of larger areas as the canopy interception is highly heterogeneous. In order to obtain a representative measure of canopy interception multiple throughfall stations must be installed. This is labor intensive and measurement uncertainties are significant. Precipitation underestimation due to wind turbulence, wetting loss, and forest debris plugging the measurement gauge at the forest floor are sources of significant uncertainty (Dunkerley, 2000).

The forest biomass represents an important resource for timber industry and renewable energy. Furthermore, forest modifies the weather through the mechanisms and feedbacks related to evapotranspiration, surface albedo and roughness. Overall, the forest ecosystems have a cooling impact on global climate as significant amounts of carbon are accumulated through photosynthesis. Carbon sequestration by afforestation and an effective forest management is a widely used method to decrease the concentration of carbon dioxide in the atmosphere and thereby attenuate the greenhouse effect (Lal, 2008). The carbon sequestration in vegetation can be quantified by monitoring the growth of biomass over time. The most conventional and accurate method to estimate forest biomass is the use of allometric models describing the relationship between the biomass of a specific tree species and easily measurable tree parameters, such as tree height and tree diameter at breast height (Jenkins et al., 2003). However, this approach is time consuming and labor intensive because numerous trees have to be surveyed to obtain accurate and representative results (Popescu, 2007). Remote sensing technology offers alternative methods to estimate biomass as high correlations are found between spectral bands and vegetation parameters. One method providing high resolution maps is airborne *Light Detection And Ranging* (LiDAR) technology (Boudreau et al., 2008). The LiDAR system is installed in small aircrafts and digitizes the first and last return of near-infrared laser recordings. The canopy height at a decimeter grid-size scale can be obtained and the biomass can be estimated from regression models. Instruments and aircraft-surveys are expensive, and measurements of tree growth will often be at a coarse temporal resolution.

Previous studies examining the effect of hydrogen on cosmic-ray neutron intensity has for most cases considered a single neutron energy range (neutron intensity measured using the moderated neutron detector) at a single height level (typically 1.5 m above the ground). Thermal and epithermal neutrons are both sensitive to hydrogen, but are characterized by very different physical properties resulting in unique responses to environmental settings and conditions at the immediate ground-atmosphere interface. For this reason, thermal and epithermal neutron intensity at multiple height levels above the ground surface are considered in this study.

The study is conducted at a forest field site using thermal and epithermal neutron measurements from bare and moderated detectors constrained with correction factor models (Andreasen et al., 2016) and modeling using the recognized and widely used Monte Carlo N-Particle transport code (MCNP) (Pelowitz, 2013). Neutron transport modeling of specific sites is limited and has only been performed for non-vegetated field sites (Franz et al., 2013b; Andreasen et al., 2016). In this context, forest sites are especially complex to conceptualize as the number of free parameters is relatively high (e.g. biomass, litter, soil chemistry, interception and the structure of the forest). Here, we first focus on modeling a forest field site. The model is developed from measured soil and vegetation parameters at the specific locality. The modeled neutron intensity profiles are evaluated against profile measurements on two different dates separated by five months, and also against time-series of neutron intensity measurements at two heights. Following, the forests environmental impact on thermal and epithermal neutron intensities are identified and quantified by applying a sensitivity analysis based on the model representative of the forest field site. In addition to improving the understanding of the environmental effect on neutron transport the focus is also on examining the potential of detecting intermediate scale canopy interception and biomass from cosmic-ray neutrons. Measurements at an agricultural field site with no biomass and at a heather field site with a smaller amount of biomass are used to underpin the influence of certain environmental variables (e.g., biomass, litter layer). To our knowledge this is the first study which provides a quantitative analysis of the potential of using the cosmic ray technique for estimation of interception and biomass.

2. Method

2.1. Terminology

The energy of a neutron determines the probability of the neutron interacting with other elements and the type of interaction (i.e. absorbing or scattering). Overall, an important threshold for the behavior of low energy neutrons is present at energies somewhere below 0.5 eV. The specific energy ranges of thermal, epithermal and fast neutrons are ambiguous. The following terminology for neutron energies is used for the purpose of this paper:

- Thermal: Energy range 0 – 0.5 eV.
- Epithermal: Energies above 0.5 eV.
- Fast: Energy range 10 - 1000 eV.

When modeling neutron transport for hydrological applications it is common to consider fast energy ranges (10 – 100 eV or 10 – 1000 eV) (Desilets et al., 2010; 2013; Rosolem et al., 2013; Franz et al., 2013b; Köhli et al., 2015), while measurements using standard soil moisture neutron detectors is sensitive to the entire epithermal energy range (Andreasen et al., 2016). Here, the term epithermal neutrons will be used for both measured neutrons of energies above 0.5 eV and modeled neutrons of energies 10 – 1000 eV.

2.2. Cosmic-ray neutron detection

2.2.1. Equipment

Cosmic-ray neutron intensity was measured using the CR1000/B system from Hydroinnova LLC, Albuquerque, New Mexico. The system has two detectors that consist of tubes filled with boron-10 (enriched to 96%) trifluoride ($^{10}BF_3$) proportional gas. The neutron detection relies on the $^{10}B(n,\alpha)^7Li$ reaction for converting thermal neutrons into charged particles (α) and then into an electronic signal. One detector is unshielded (bare detector), while the other is shielded by 25 mm of high-density polyethylene (moderated detector). These different configurations give the bare and moderated tubes different energy sensitivities.

The thermal neutron absorption cross-section of ^{10}B is very high (3835 barns) (Sears et al., 1992). This absorption cross-section decreases rapidly with increasing neutron energy following a $1/E_n^{0.5}$ law (where E_n is neutron energy) (Knoll 2010). Therefore, the energies measured by the bare tube comprise a continuous distribution which is heavily weighted toward thermal neutrons (<0.5 eV), with a small proportion of epithermal neutrons also being detected (<10%) (Andreasen et al., 2016).

The moderated detector is more sensitive to higher neutron energies (> 0.5 eV). The purpose of the polyethylene is to slow (moderate) epithermal neutrons through interactions with hydrogen in order to increase the probability of them being captured by ^{10}B in the detector. At the same time the polyethylene attenuates the thermal neutron flux through neutron capture by hydrogen. Nonetheless, a large proportion (approximately 40% of the thermal neutrons detected by the bare detector) originates from below 0.5 eV (Andreasen et al., 2016).

Obeying Poissonian statistics (Knoll 2010) the measurement uncertainty of a given neutron intensity, N, decreases with increasing neutron intensity and the standard deviation equals $N^{0.5}$.

The measured neutron intensities are corrected for variations in barometric pressure, atmospheric water vapor and incoming cosmic-ray intensity following procedures of Zreda et al. (2012) and Rosolem et al. (2013). Unfortunately, the water vapor correction of Rosolem et al. (2013) is only valid for epithermal neutron measurements. Since the development of correction methods is beyond the scope of this study, we refrained from using a vapor correction for the measured thermal neutron intensities. We believe that this missing correction will only have a minor effect on our results (Andreasen et al., 2016). Nevertheless, we suggest that future studies should investigate the effect of water vapor on thermal neutron intensities and to develop appropriate correction methods.

2.2.2. Pure thermal and epithermal neutron detection

We expect thermal and epithermal neutrons to have unique responses to environmental properties and settings. Therefore, it is important to consider pure signals of thermal and epithermal neutrons, and not simply the raw neutron intensity signal measured by the bare and moderated detectors. In order to limit the epithermal and thermal neutron contribution to the bare and the moderated detectors, respectively, we use the cadmium-difference method (Knoll, 2010; Glasstone and Edlund, 1952). The thermal absorption cross-section of cadmium is very high (approximately 3500 barns) for neutron energies below 0.5 eV. The cross-section drops to approximately 6.5 barns at neutron energy 0.5 eV and remains low with increasing neutron energies. Thus, a cadmium shielded neutron detector only measures neutrons of energies higher than 0.5 eV. The epithermal neutron intensity was measured from a cadmium shielded moderated detector, while the thermal neutron intensity was calculated by subtracting the neutron intensity measured by the cadmium-shielded bare detector from the neutron intensity measured by the bare detector (unshielded). The cadmium-difference method is described in Andreasen et al. (2016) in detail.

Appropriate neutron energy correction models were applied in order to obtain pure thermal and pure epithermal neutron intensity measurements for the time periods when the cadmium-difference method was not applied (Andreasen et al., 2016). The neutron energy correction models were obtained from field campaigns applying the cadmium-difference method on bare and moderated detectors at various locations (height levels and land covers). The determination of the neutron energy correction models was based on the relationships of measurements from unshielded and shielded neutron detectors (Andreasen et al., 2016).

2.2.3. Footprint

The footprint of the bare detector is unexplained, while the footprint of the moderated detector was determined from modeling by Desilets and Zreda (2013) and Köhli et al. (2015). However the findings of these two studies were inconsistent. Desilets and Zreda (2013) used the neutron transport code Monte Carlo N-Particle eXtended (MCNPx) and found the footprint to be nearly 600 m in diameter in dry air, while Köhli et al. (2015) using the Ultra Rapid Adaptable Neutron-Only Simulation (URANOS) estimated the footprint to be 260 – 480 m in diameter depending on the air humidity, soil moisture and vegetation. The potential mismatch in the footprint of the bare and the moderated detectors is a concern when combining the neutron intensity measurements. Nevertheless, the environmental conditions at the field sites are fairly homogeneous and although the footprint might be different as a first approximation we assume the neutron intensity measured using the bare and the moderated detector are comparable.

2.2.4. Field measurements

Three field sites are used in this study; the primary site is Gludsted Plantation, and two secondary sites are Voulund Farmland and Harrild Heathland. The sites located within the Skjern River Catchment in the Western part of Denmark represents the three major land use types (Figure 1) and are all part of the Danish hydrological observatory (HOBE) (Jensen and Illangasekare, 2011). The sites are situated at an elevation of approximately 50 - 60 m above sea level on an outwash plain from the last glaciation composed of nutrient depleted sandy stratified soils. Harrild Heathland is located 1 km south of Voulund Farmland, both approximately 10 km west of Gludsted Plantation.

Figure 1 is inserted here

Gludsted Plantation forest field site (56°04'24"N 9°20'06"E) is situated within a coniferous forest plantation covering an area of around 3500 ha. The trees of the plantation are densely planted in rows and are in general composed of Norway spruce with small patches of Sitka spruce, Larch and Douglas fir. Within the field site area (38 ha) the trees were estimated to be up to 25 m high and the dry above-ground biomass to be around 100±46 t/ha (one standard deviation) using LiDAR images from 2006 and 2007 (Nord-Larsen and Schumacher, 2012). The dry below-ground biomass was calculated to be 25 t/ha using a root-to-shoot ratio (the weight of the roots to the weight of the aerial part of the tree) for Norway spruce of 0.25 (Levy et al., 2004). Information on the vegetation at the forest field site (e.g. tree species, ages, heights and trunk diameters) is acquired from a register managed by The Danish Nature Agency (representative of the 2012 conditions); see Table 2.

Table 2 is inserted here

In Scandinavian forests around 79% of the total above-ground biomass of Norway spruce is stored within the tree trunks. The remaining 21% is found in the branches and needles (termed *foliage*). A typical density of the tree trunk is 0.83 g/cm^3 (Serup et al., 2002). The major component of the tree biomass is cellulose ($C_6H_{10}O_5$) and represents around 55% of the total mass, while the remaining 45% is vegetation water (Serup et al., 2002). Based on these approximations, the wet above- and below-ground biomass at the field site area are estimated to be 182 t/ha and 45 t/ha, respectively. With a leaf area index (LAI) of 4.5 and a canopy interception capacity coefficient of 0.5 mm/LAI (Andreasen et al., 2013) the maximum storage of canopy intercepted rain is estimated to be 2.25 mm.

Soil samples were collected within the footprint of the cosmic-ray neutron detector on August 26 – 27, 2013 following the procedure of Franz et al. (2012). Based on these samples the organic rich litter layer is found to be 5 - 10 cm thick. The dry bulk density of the litter and mineral layer are calculated by oven drying the soil samples (Table 2), and the soil organic matter content of the mineral soil is determined from the loss-on-ignition method (16.9% in 10 - 20 cm depth and 7.6% in 20 - 30 cm depth). A time series of soil moisture is calculated from cosmic-ray neutron intensity, starting in spring, 2013, using the N_0-method as presented in Desilets et al. (2010). Lastly, the chemical composition of the soil matrix is estimated for two random soil samples collected at 20-25 cm depth using the *X-ray fluorescence* (XRF) analysis (Table 3).

Table 3 is inserted here

The element Gadolinium (Gd) can have a significant impact on thermal neutron intensity even at low concentrations due to its very high absorption cross-section of 49000 barns (1 barn = 10^{-24} cm^2). The detection limit of the XRF in this study is 50 ppm for gadolinium (Gd). The two soil samples from Gludsted Plantation both have Gd concentration below the detection limit of the XRF. Inductively coupled plasma mass spectrometry (ICP-MS) detects metals and several non-metals at very small concentrations and was used to characterize the soil chemistry of a nearby field site with similar soil conditions

(Salminen et al., 2005). A Gd concentration of 0.51 ppm was found at that site and we assume this value to be representative of the conditions at Gludsted Plantation.

Gludsted Plantation is a heavily equipped research field site with a 38-m high tower for measurements at multiple heights within the forest canopy. At Gludsted Plantation, CR1000/B systems were installed at ground level (1.5 m height) and canopy level (27.5 m height) in the spring of 2013. Hourly neutron intensities have been continuously detected (Andreasen et al., 2016) except for short periods where the detectors were used for other types of measurements or during times of malfunctions. Neutron intensity profiles extending from the ground surface to 35-m-height above the ground were measured at approximately 5 m-increments during two field campaigns on November 28 – 29, 2013 and March 12 - 14, 2014 at Gludsted Plantation. In order to obtain comparability between measurements and modeling pure thermal and epithermal neutron signals were estimated using neutron energy correction models on measurements from bare and moderated detectors, respectively. The neutron energy correction models were both used on time-series and neutron height profile measurements. Additionally, during the field campaign on March 12 -14, 2014 an epithermal neutron intensity profile (with no thermal contribution) was measured using a cadmium-shielded moderated detector (Andreasen et al., 2016). For the profile measurements neutron intensities were recorded at a 10-minute time resolution. As the thermal neutron intensity decreases significantly with height we choose to extend the time of measurement with the height level increments to maintain a low and consistent measurement uncertainty. The volumetric soil moisture content measured using the cosmic-ray neutron method (Zreda et al., 2008) was 0.18 during both field campaigns.

Voulund Farmland (56°02'14"N 9°09'38"E) is an agricultural field site. In 2015, the fields were cropped with spring barley. After harvest in the late summer until ploughing in spring 2016 (prior to sowing) the fields were covered with stubble (around 10 cm high). A 25 cm layer of relatively organic rich soil (4.45% soil organic matter) is found at the top of the soil column and is a result of the cultivation practices. More information about the field site can be found in Andreasen et al. (2016). Ground level neutron intensities were measured on September 22 and 23, 2015 at Voulund Farmland (Andreasen et al., 2016). The measurements were conducted using the bare and the moderated neutron detectors normally installed at Gludsted Plantation and data were logged every 10 minutes. In order to obtain pure thermal and epithermal neutron height profiles the neutron energy correction models were applied.

Harrild Heathland (56°01'33"N 9°09'29"E) is a shrub land field site dominated by grasses and heather. The heathland is maintained by controlled burning, yet, the field site area has not recently been burnt. The organic rich litter layer is found to be around 10 cm thick during soil sampling field campaigns at the field site. Due to podsolization a low permeable hardpan-layer hindering percolation to deeper depths is present at around 25-30 cm depth. In the period from October 27 to November 16, 2015 the ground level thermal and epithermal neutron intensity was measured directly at Harrild Heathland using the cadmium-difference method (Knoll, 2010). The cadmium-difference method was applied using two bare and one moderated detector normally installed at Gludsted Plantation. The neutron intensity was integrated and recorded on an hourly basis.

2.3. Neutron transport modeling

The three-dimensional Monte Carlo N-Particle transport code version 6 (MCNP6) (Pelowitz, 2013) simulating thermal and epithermal neutrons is used to model the forest field site. The code holds libraries of measured absorption and scattering cross-sections used to compute the probability of interactions between earth elements and neutrons. The MCNP6 combines Monte Carlo N-Particle Transport code version 5 (MCNP5) and Monte Carlo N-Particle Extended Radiation Transport code (MCNPX). MCNPX has been used for most neutron transport modeling within the field of hydrology (Desilets et al., 2013; Rosolem et al., 2013; Zweck et al., 2013). However, the improved and more advanced MCNP6 has recently been introduced and provided more realistic neutron intensity profiles for Voulund Farmland field site (Andreasen et al., 2016).

The number of particle histories released at the center of the upper boundary of the model domain is specified to obtain an uncertainty below 1%. The released particles represent a distribution of high-energy particles typical for the spectrum of incoming cosmic-rays traveling through the atmosphere. The modeled neutron intensities are normalized per unit source particle providing relative values (Zweck et al., 2013). In order to obtain values comparable to measurements conversion factors are used (Andreasen et al., 2016). The conversion factors 3.739×10^{12} and 1.601×10^{13} are multiplied by the modeled thermal neutron fluences in the energy range of 0 – 0.5 eV and epithermal neutron fluences in the energy range 10 – 1000 eV, respectively. We stress that, the conversion factors are detector-specific as well as dependent on the horizontal area of the model-setup in MCNP6. The dependence of the environmental settings is at this point in time unclear and should be addressed in future studies.

2.3.1. The Gludsted Plantation reference model

The model domain of MCNP6 is defined by cells of varying geometry, and each cell is assigned a specific chemical composition and density. The lowest 4 m of the Gludsted Plantation reference model consists of subsurface layers. The chemical composition of the mineral soil is prescribed according to the chemical composition from XRF measurements; assumed Gd concentration of 0.51 ppm, wet below-ground biomass (cellulose) of 45 t/ha, dry bulk density of 1.09 g/cm^3 and soil moisture content of 0.18. The litter layer is defined according to the chemical composition of cellulose, dry bulk density of 0.34 g/cm^3 and moisture content similar to that of mineral soil (see also Table 3). The same soil moisture was used for the whole soil column, as the soil moisture profile was unknown for the days of neutron profile measurements, and furthermore we wanted to test the signal of soil moisture. The atmosphere is composed of 79% nitrogen and 21% oxygen by volume and extends from the forest canopy surface to the upper boundary of the model domain at approximately 2 km height. Here, an incoming spectrum adapted to the specific level of the atmosphere is specified (Hughes and Marsden, 1966). The density of air is assumed to be 0.001165 g/cm^3. Multiple sublayers of varying vertical discretization cover the vertical extent of the model in order to record neutron intensities at multiple heights and depths from the ground surface. The resolution of the layers increases with proximity to the ground surface ranging in thickness from 0.025 m to 0.20 m for the subsurface layers and from 1 m to 164 m for the layers above the ground surface. 1 m layers are used from the ground to 28 m height to enable neutron intensity to be modeled at the measured heights. The neutron intensity detectors are layers of 1 m height and extent the full lateral model domain (400 m x 400 m). Reflecting surfaces constrain the model domain. Thus, the particles reaching a model boundary will be reflected specularly back into the model domain. Wet above-ground biomass of 182 t/ha is distributed within the forest canopy layers extending from the ground surface to 25 m above the ground (Table 4).

The proper way to conceptualize the forest canopy in the model-setup is not obvious and the sensitivity to forest representation on neutron intensity is therefore investigated using four model-setups of increasing complexity. In the first representation (Model *Foliage*; Figure 2B) the same material composed of cellulose and air (foliage) is assigned all forest canopy layers. In order to obtain a wet above-ground biomass of 182 t/ha a relatively low density of 0.00189 g/cm^3 is calculated for the material. In order to allow for a forest canopy layer to be composed of multiple materials (cellulose and air) and densities (massive tree trunks and less dense foliage and air), the horizontal discretization of the forest canopy layers is reduced to smaller cells for the next tree model-setups. The bole of each tree is for all three model-setups represented by a cylinder with a diameter of 0.14 m, a composition of cellulose, and a density of 0.83 g/cm^3. A tree is placed at the center of each cell and extends from the ground surface to the top of the forest canopy layer. In the second representation (Model *Tree trunk, Air*; Figure 2C) the horizontal discretization of the forest canopy layers is set to 4.20 m by 4.20 m and the remaining volume beyond the bole of the tree is made of air alone (density 0.001165 g/cm^3). Thus, for this model all biomass is stored in the bole of the trees and the cell size is adjusted to obtain a wet above-ground biomass of 182 t/ha resulting in 9070 trees within the model domain. In the third representation (Model *Tree trunk, Foliage*; Figure 2D) the horizontal discretization of the forest canopy layers is 4.72 m by 4.72 m and the remaining volume beyond the bole of the tree is made of foliage. As previously described, the share of biomass stored in the tree trunk and the foliage is 79% and 21%, respectively, typical of Norway spruce. The foliage material is a composite of cellulose and air and the density is the sum of the two (0.001318 g/cm^3). A total of 7182 trees are evenly spaced within the model domain. The fourth and most complex forest canopy conceptualization (Model *Tree trunk, Foliage*; Figure 2E) is equal to the Model *Tree trunk, Foliage* except that air is also included in the description of the forest canopy layers and the density of the foliage is increased to obtain the same above-ground biomass as for the other models. The foliage is specified as a 1.7 m thick band around the tree cylinder and the density of foliage material composted of air and cellulose is 0.00151 g/cm^3.

Table 4 and Figure 2 are inserted here

2.3.2. Sensitivity to environmental conditions

The sensitivity of thermal and epithermal neutron intensities to soil moisture is examined using modeling. The soil moisture in the Gludsted Plantation reference model is specified to 0.18 and both drier and wetter soils are modeled to test the sensitivity, i.e. 0.05, 0.10, 0.25, 0.35 and 0.45. Both the forest canopy conceptualization of Model *Tree trunk, Foliage, Air* and the Model *Foliage* are used.

The thermal and epithermal neutron intensity is both a product of hydrogen abundance as well as elemental composition. The Gludsted Plantation reference model including a complex forest conceptualization (Model *Tree trunk, Foliage, Air)* is used to test the sensitivity of thermal and epithermal neutron intensities to soil chemistry. The Gludsted Plantation reference model holds the most complex soil chemistry (*fourth order complexity*) with multiple subsurface layers composed of measured concentrations of major elements determined by XRF, soil organic matter, gadolinium and roots (Table 3). In order to test the effect of simplifying the soil chemistry a component is excluded one at the time: 1) *third order complexity*; soil organic matter is excluded, 2) *second order complexity*; soil organic matter and roots are excluded, 3) *first order complexity*; soil organic matter, roots and gadolinium are excluded, and 4) *pure* SiO_2; all other components are excluded.

The sensitivity of the modeled thermal and epithermal neutron intensities to the presence of the organic litter layer is investigated using the Gludsted Plantation reference model including a complex forest conceptualization (Model *Tree trunk, Foliage, Air),* in which the thickness of the litter layer is set to be 10.0 cm. Sensitivity simulations are carried out for the following thicknesses of the litter layer: 0.0 cm, 2.5 cm, 5.0 cm and 7.5 cm. For all litter layer models, the total thickness of the subsurface is kept constant at 4 m.

The materials of forest floor litter and mineral soil differ distinctly in terms of chemical composition and dry bulk density. The determination of dry bulk density of the two materials is characterized by measurement uncertainty, especially for the litter as sampling and drying is very challenging for materials including large amounts of soil organic matter (O'Kelly, 2004). Given that the elemental composition and density of the soil matrix is relevant for the neutron intensity the sensitivity of dry bulk density on thermal and epithermal neutron intensity is examined. The dry bulk density of the Gludsted Plantation reference model is set to 0.34 g/cm^3 for the litter layer and 1.09 g/cm^3 for the mineral soil. The Gludsted Plantation reference model including the complex forest conceptualization (Model *Tree trunk, Foliage, Air)* is used to test the sensitivity applying four scenarios: 1) higher dry bulk density of the litter layer (0.50 g/cm^3), 2) higher dry bulk density of the mineral soil (1.60 g/cm^3), 3) lower dry bulk density of the litter layer (0.20 g/cm^3), and 4) lower dry bulk density of the mineral soil (0.60 g/cm^3). All values with the exception of higher dry bulk density of 1.60 g/cm^3 for the mineral soil (standard value for quartz; soil particle density of 2.66 g/cm^3 and a porosity of 0.40) are within the range of the measurements (see Table 2).

The Gludsted Plantation reference model including the complex forest conceptualization (Model *Tree trunk, Foliage, Air)* is used to test the sensitivity to canopy interception by increasing the density and water content of the cells described by foliage material. The forest canopy of the reference model is dry (foliage material density 0.00151 g/cm^3). In order to test the effect, water equivalent to 1 mm (foliage material density 0.00155 g/cm^3), 2 mm (foliage material density 0.00159 g/cm^3) and 4 mm (foliage material density 0.00167 g/cm^3) of canopy interception is added to the foliage volume.

The sensitivity to biomass is investigated using the Gludsted Plantation reference model with the complex forest conceptualization (Model *Tree trunk, Foliage, Air*) and the simplified model-setup (Model *Foliage*). The biomass of the Gludsted Plantation reference model is equivalent to a dry above-ground biomass of 100 t/ha and a dry below-ground biomass of 25 t/ha, following the root-to-shoot ratio of 0.25 typical of Norway spruce. This distribution is used for both model setups. For the sensitivity analysis one model without vegetation (Model *0 t/ha*, Figure 2A) and three models with different amounts of biomass are used (see Table 4). The forest canopy layer extending uniformly from the ground to 25 m above the ground surface is for the model with no vegetation assigned with the material composition and density of air. The amount of biomass modeled for the three remaining models is equivalent to a dry above-ground biomass of: 1) 50 t/ha, 2)

200 t/ha, and 3) 400 t/ha. The size of the cells in the forest layers and the density of the foliage material are adjusted in order to obtain the correct amount of biomass.

3. Results and discussions

3.1. Gludsted Plantation

The neutron intensity profiles for Gludsted Plantation are modeled using four different forest canopy conceptualizations. The model results are presented in Fig. 3 along with time-series of hourly and daily ranges of thermal and epithermal neutron intensities collected at the Gludsted Plantation during the period 2013-2015, and measured/estimated thermal and epithermal neutron intensity profiles (November 2013 and March 2014). Following the Poissonian statistics the relative uncertainty decreases with increasing neutron intensity. The relative measurement uncertainty is therefore higher for the hourly time series data than for the multi-hourly (2-12 hr) and daily measurements. Accordingly, we choose to rely mostly on the time-series measurements, as the measurement uncertainty is lower than for the neutron height profiles.

Figure 3 is inserted here

Overall, time-series and profile measurements provide similar results in agreement with theory. The thermal neutron intensity decreases considerable with height above ground surface and is at canopy level reduced by around 50% compared to at the ground level. The epithermal neutron intensity increases slightly with height and is around 10-15% higher at the canopy level compared to the ground level. Still, some differences are observed between the neutron height profiles measured in November 2013 and March 2014. The soil moisture was similar during the time of neutron profile detection and we expected the differences to be a result of different climate and weather conditions related to the seasons of detections (spring and fall). Furthermore, although the area average soil moisture is the same for the two field campaigns the soil moisture profiles may be different resulting in different neutron profile slopes and thermal-to-epithermal neutron (t/e) ratios. In particular, the assumption of identical soil moisture of the litter layer and the mineral soil may be inappropriate as this was not the case during two out of three soil sampling field campaigns where the results differed considerably (soil samples were collected at 18 locations within a circle of 200 m in radius and in 6 depths from 0-30 cm depth following the procedure of Franz et al. (2012)). However, both neutron profiles are within the ranges of the daily time-series measurements and we therefore still believe that they can be used in the assessment of the modeled neutron profiles. For future studies we recommend soil sample field campaigns to be conducted on the days of neutron profile measurements.

Overall, a remarkable agreement between measured and modeled neutron intensities is seen in Fig. 3. We stress that no calibration of the governing physical properties in the forest model is performed and that the estimates are based on measured properties. The ground and canopy level thermal and epithermal neutron intensity for the four forest canopy conceptualization models are provided in Table 5. All modeled neutron intensity profiles are within the range of hourly time-series measurements, and in particular the thermal neutron profiles are in agreement with measurements. Overall, the models of the more complex forest canopy conceptualizations, including a tree trunk, provide similar thermal and epithermal neutron profiles. The ground and canopy level thermal neutron intensity of models with forest canopy conceptualization of Model *Tree trunk, Foliage* and Model *Tree trunk, Foliage, Air* are within the daily ranges of the time-series measurements. In contrast, the modeled epithermal neutron profiles of the more complex models are slightly underestimated and the profile slope is steeper than the measured profiles. Nevertheless, the modeled epithermal neutron intensity profile is still within the ranges of the time-series of hourly measurements at both height levels. The neutron intensity profiles of the simpler forest canopy conceptualization of Model *Foliage* is less steep and is the only model providing an epithermal neutron intensity profile within the daily ranges of the time-series measurements at both the ground and canopy level.

Table 5 is inserted here

The most appropriate forest canopy conceptualization is not obvious from Fig. 3 as the best fit of the thermal measurements is found using a complex conceptualization, while the more simple foliage conceptualization matches the epithermal measurements better. We can, however, conclude that the neutron transport at the ground-atmosphere interface is sensitive to the level of complexity of the forest canopy conceptualization. Improved comparability to measurements may be obtained by advancing the forest canopy conceptualization. Currently, one tree is defined and repeated throughout the model domain. The trees are placed in even rows and the same settings are applied from the ground surface to 25 m height. In order to advance the forest canopy conceptualization, trees of different heights and diameters could be included, and the placement of the trees could be more according to the actual placement of trees at the forest field site. Additionally, variability in tree trunk diameter, foliage density and volume with height above the ground surface could be implemented.

Here, a sensitivity analysis is perform using the most complex model and occasionally the simplest forest canopy conceptualization to examine the effect of soil moisture, soil dry bulk density and composition, litter and mineral soil layer thickness, canopy interception and biomass on the thermal and epithermal neutron transport at the immediate ground-atmosphere interface.

3.2. Soil moisture

The modeled thermal and epithermal neutron intensity profiles of Model *Tree trunk, Foliage, Air* and Model *Foliage* using six different soil moistures, 0.05, 0.10, 0.18, 0.25, 0.35 and 0.45, are presented in Figs. 4 and 5, respectively. To enable comparison the measurements included in Fig. 3 are also included in Figs. 4 and 5. The sensitivity of soil moisture on thermal and epithermal neutron intensities at the ground and canopy level relative to the Model *Tree trunk, Foliage, Air* and Model *Foliage* at reference conditions (soil moisture 0.18) is provided in Table 6.

Figure 4, Figure 5 and Table 6 are inserted here

As expected, the thermal and epithermal neutron intensity is seen in Table 6, Figs. 4 and 5 to decrease with increasing soil moisture. For both model-setups, the largest changes in neutron intensity occur at the dry end of the soil moisture range and for the epithermal neutrons. For Model *Tree trunk, Foliage, Air* (Figure 4), only a minor decrease in the sensitivity of soil moisture on epithermal neutron intensity is observed going from ground level to canopy level (approximately 15%

reduction in intensity range corresponding to a soil moisture change of 0.40). On the other hand, the sensitivity of the thermal neutron intensity is reduced more than 50% (Table 6) most likely caused by the lower mean-free path length of the thermal neutrons compared to that of epithermal neutrons. The response to soil moisture is similar for the model with a simple forest canopy conceptualization (Figure 5). However, both thermal and epithermal neutron intensities are found to be slightly more sensitivity to soil moisture. Neutron intensity at dry and wet soil conditions is represented by the range of time-series neutron intensity measurements. Overall, the modeled neutron intensities are within the measurement range and the more appropriate model-setup for Gludsted Plantation is not obvious from the modeling results.

3.3. Subsurface properties

Thermal and epithermal neutron intensity profiles are modeled using Model *Tree trunk, Foliage, Air* (with *fourth order complexity*) and models of decreasingly complex soil. Soil organic matter, below-ground biomass, Gd and the chemical composition from XRF measurements are excluded one at the time (from *third* to *first order complexity*) and the final model includes a simple silica soil (SiO_2). The exact sensitivity of excluding the different components on ground and canopy level thermal and epithermal neutron intensity is quantified in Table 6 (see values in parentheses). Only the removal of soil organic matter (*third order complexity*) changes the neutron intensity significantly at Gludsted Plantation, i.e. an increase in the ground level thermal and epithermal neutron intensity of 19 cts/hr (cts = counts) and 25 cts/hr, respectively, is observed. The sensitivity to soil chemistry on thermal and epithermal neutron intensity profiles was found to be more substantial at Voulund Farmland (Andreasen et al., 2016). The soil organic matter content at Voulund Farmland is smaller and the soil chemistry is, except from a few elements (added in relation to farming activities; spreading of manure and agricultural lime), similar to Gludsted Plantation. Modelling shows that the sensitivity to soil chemistry at Gludsted Plantation is dampened by the considerable amount of hydrogen present in the forest biomass and the litter at the forest floor (not presented here).

The thermal and epithermal neutron intensity is modeled for a forest with litter layer of various thicknesses (Figure 6A). The Model *Tree trunk, Foliage, Air* including a 10.0 cm thick litter layer is used along with forest models with litter layers of 0.0 cm, 2.5 cm, 5.0 cm and 7.5 cm thickness.

Figure 6 is inserted here

Neutron intensities are found to decrease with an increasing layer of litter, having the greatest impact on the epithermal neutron intensities (see also Table 6). The considerable amount of hydrogen in litter causes the probability of scattering of neutrons travelling through the subsurface to increase with increasing amounts of litter. Thereby, the t/e is found to be altered when changing the thickness of the litter layer. This effect is most pronounced when the model without a litter layer is compared to the model with just a thin 2.5 cm thick litter layer. Additionally, the sensitivity to litter and mineral soils dry bulk density on neutron intensity is examined as a considerable range of values is measured within the footprint of the neutron detector (see Table 2). Models including higher litter layer (0.50 g cm^{-3}) and mineral soil dry bulk density (1.60 g cm^{-3}) as well as lower litter layer (0.20 g cm^{-3}) and mineral soil dry bulk density (0.60 g cm^{-3}) only provided slight changes in thermal and epithermal neutron intensities. Nevertheless, a reverse response of changed bulk densities is observed. A decrease in neutron intensity is obtained both by increasing the dry bulk density of the litter material and decreasing the dry bulk density of the mineral soil. Conversely, higher neutron intensities are computed by decreasing the dry bulk density of the litter material and increasing the dry bulk density of the mineral soil. The production rate of low-energy neutrons (<1 MeV) per incident high-energy neutron is higher for interactions with elements of higher atomic mass ($A^{2/3}$, where A is the atomic mass) (Zreda et al., 2012). Heavier elements are in particular found in mineral soil and an increase in the dry bulk density entails a higher production rate and therefore higher neutron intensity. The concentration of hydrogen is increased with an increased dry bulk density of litter material resulting in a greater moderation and absorption of neutrons, and as a consequence lower neutron intensities. To summarize, the mineral soil acts as a producer of thermal and epithermal neutrons, while the litter acts as an absorber.

3.4. Canopy interception

The effect of canopy interception on thermal and epithermal neutron intensity is modeled using Model *Tree trunk, Foliage, Air* (Figure 6B and Table 6). Except for a slight increase in ground level thermal neutron intensities with wetting of the forest canopy, no effect of canopy interception on ground and canopy level thermal and epithermal neutron intensity is observed. A maximum change of approximately 3% (15 cts/hr) is observed for thermal neutron intensity at ground level going from a dry canopy to 4 mm of canopy interception. At the specific field site a maximum canopy storage capacity of 2.25 mm is expected, producing a change in observed ground level thermal neutron intensity of approximately 7 cts/hr. Given an average neutron intensity of 504 cts/hr of ground level thermal neutrons with the installed detectors, an uncertainty of 22 cts/hr is expected based solely on Poissonian statistics. In order to obtain a signal-to-noise ratio of 1, either an 11-hour-integration time or 11 detectors similar to the installed are needed. However, longer integration times are not appropriate when considering Gludsted Plantation as the return time of canopy interception (cycling between precipitation and evaporation) often is short (half-hourly to hourly time resolution).

Although detection of canopy interception at Gludsted Plantation is unfavorable it may still be possible at more appropriate conditions. Canopy interception modeling as described above is therefore also performed for soil moisture 0.05, 0.10, 0.25 and 0.40. Ground level t/e ratio of the 20 model combinations are plotted against ground level thermal neutron intensity, ground level epithermal neutron intensity and volumetric soil moisture (Figure 7). We choose not to include measurements in the figure because the measurement uncertainty at a relevant integration time is greater than the signal of canopy interception.

Figure 7 is inserted here

Overall, ground level t/e ratio is found to be independent of ground level thermal neutron intensity (Figure 7A), ground level epithermal neutron intensity (Figure 7B) and volumetric soil moisture (Figure 7C). Ground level t/e ratio is found to increase with increasing canopy interception. The ground level t/e ratio for a dry canopy is on average 0.804, while the average at 4 mm of canopy interception is 0.836. Overall, the same increase in ground level t/e ratio is obtained per 1 mm additional canopy interception. Although the change in the t/e ratio with wetting/drying of the forest canopy is small the canopy interception may potentially be measured using cosmic-ray neutron intensity detectors at locations with: 1) a high neutron intensity level (lower latitude and/or higher altitude, 2) more sensitive neutron detectors, and 3) greater amounts of canopy interception with longer residence time (e.g. snow). We suggest future studies investigating the effect of canopy interception on the neutron intensity signal to be performed at locations matching one or more of these criteria.

3.5. Biomass

The sensitivity to the amount of forest biomass on thermal and epithermal neutron intensity using the forest canopy conceptualization of Model *Tree trunk, Foliage, Air* and Model *Foliage* are presented in Fig. 6C and Fig 6D, respectively. The neutron intensity is provided for a scenario with no vegetation and models with biomass equivalent to dry above-ground biomass of: 50 t/ha, 100 t/ha (Gludsted Plantation), 200 t/ha and 400 t/ha.

Forest biomass is seen to significantly alter the thermal and epithermal neutron intensity both with regards to the differences between ground and canopy level neutron intensity, and ground level t/e ratios (Figures 6C and 6D). The direction and magnitude of these changes are found to be rather different depending on the two forest canopy conceptualizations. For the Model *Tree trunk, Foliage, Air* the increase in biomass results in an increase in thermal neutron intensity while the epithermal neutron intensity decreases (Figure 6C). The neutron intensity depends on how many neutrons are produced, down-scattered to lower energies and absorbed. Including biomass to a system increases the concentration of hydrogen and leads to reduced neutron intensity as the moderation and absorption is intensified. Despite this, increased thermal neutron intensity is provided with greater amounts of forest biomass. We hypothesize that forest biomass enhances the rate of moderation more than the rate of absorption. Thus higher thermal neutron intensity is obtained as the number of thermal neutrons generated by the moderation of epithermal neutrons exceeds the number of thermal neutrons absorbed. This behavior may be due to the large volume of air within the forest canopy. The probability of thermal neutrons to interact with elements within this space is low as the density of air is low. The effect at ground level is almost the same up to an elevation of 20 m, but decreases sharply near the top of the forest canopy (not presented here).

Increasing the biomass in the Model *Foliage* from 0 t/ha to 50 t/ha (Figure 6D) results in a considerable increase in ground level thermal neutron intensity (136 cts/hrs, Table 6) while at canopy level thermal neutron intensity is almost unaltered. A further increase in biomass (>50 t/ha) decreases both ground and canopy level thermal neutron intensities. The epithermal neutron intensity decreases at ground level and increase proportionally at canopy level with increasing amounts of biomass. The epithermal neutrons produced in the ground escape to the air and are moderated by the biomass, resulting in reduced epithermal neutron intensity with greater amounts of biomass. All models provide in accordance to theory increasing epithermal neutron intensity with height, yet, the reduced steepness of the neutron height profiles with added biomass is unexplained. Oppositely to Model *Tree trunk, Foliage, Air*, the ground level thermal neutron intensity decreases with added biomass. This may be due to the elemental concentration. Here, no space is occupied by a material of very low elemental density and may lead to an increased absorption of thermal neutrons.

As shown in Figs. 3, 6C and 6D the resulting thermal and epithermal neutron intensity profiles depend highly on the chosen model-setup (forest conceptualization). At this stage, we cannot determine which conceptualization is more realistic, and we therefore choose to use both conceptualizations in the further analysis.

Overall, a positive correlation is found for the differences between ground and canopy level neutron intensity (thermal and epithermal neutron energies) and the amount of biomass (Figures 6C and 6D, and Table 6). However, the Model *Tree trunk, Foliage, Air* and Model *Foliage* provides different relationships, and measurements and modeling are not fully in agreement. Alternatively, one can also potentially use the t/e ratio at the ground level to assess biomass. The advantage is that only one station is needed - and that at a convenient location. This would also allow for surveys of biomass estimations to be conducted from mobile cosmic-ray neutron intensity detector systems, e.g. installed in vehicles.

The measured and modeled ratios are again provided using both forest canopy conceptualization, i.e. Model *Tree trunk, Foliage, Air* (Figure 8) and Model *Foliage* (Figure 9). The ratios are plotted against A) ground level thermal neutron intensity, B) ground level epithermal neutron intensity, and C) soil moisture estimated using the N_0-method (Desilets et al., 2010). Measurements are provided as daily averages, biweekly averages and as a total average of the whole two-year-period.

Figure 8 and Figure 9 are inserted here

The modeled ground level t/e ratio increases with forest biomass (Figures 8 and 9). Drying or wetting of soil change the thermal and epithermal neutron intensity proportionally and the ratios are accordingly found to be independent of changes in the ground level thermal neutron intensity, the ground level epithermal neutron intensity and volumetric soil moisture. However, this independence is not seen in the measurements, where the ground level epithermal neutron intensity and soil moisture (Figures 8C and 9C) in particular seem to impact the ratio. The discrepancy of measurements and modeling could be related to: 1) shortcomings in the model setup, i.e. a need for an even more realistic forest conceptualization, and more detailed and up-to-date forest information. A model including a sufficient representation of the field site will provide neutron height profiles and t/e ratios more representative of the real conditions, 2) discrepancy of measured and modeled energy ranges as discussed in Andreasen et al. (2016), and 3) unrepresentative biomass estimate. The 100 t/ha dry above-ground biomass was estimated using LiDAR images from 2006 and 2007 and therefore not completely representative of the 2013-2015 conditions (because of tree growth). Furthermore, the biomass estimate varied considerably within the image (standard deviation = 46 t/ha), and the image coverage did not fully match the footprint of the cosmic-ray neutron intensity detector.

Overall, for the Model *Tree trunk, Foliage, Air* in Fig. 8, a remarkable agreement is seen when comparing the two-year-average of the measured ratio with the modeled value of Gludsted Plantation (100 t/ha dry above-ground biomass, Figure 8). The biweekly averages of measurements are all within the ratios modeled for biomass of 50 t/ha - 200 t/ha. For the Model *Foliage* in Fig. 9 the measured ratio is in better agreement with a lower biomass (50 t/ha dry above-ground biomass) and the biweekly averages of the measurements are much wider exceeding both the lower and upper boundary of ratios provided by the models of 50 t/ha and 400 t/ha dry above-ground biomass.

A fairly proportional increase in the ground level t/e ratio with respect to greater amounts of biomass is found when using Model *Tree trunk, Foliage, Air* (Figure 10). Contrarily, when using Model *Foliage*, a more uneven increase in the ratio with increasing amounts of biomass is provided. A major increase in the ground level t/e ratio of around 0.22 appears from no vegetation to a dry above-ground biomass of 50 t/ha. However, additional amounts of biomass only increase the ground level t/e ratio slightly. With additional 350 t/ha biomass (from 50 t/ha to 400 t/ha dry above-ground biomass) the t/e ratio increases by only 0.05 cts/hr.

Figure 10 is inserted here

The modeled ground level t/e ratio is compared with two additional field sites close to Gludsted Plantation. The three field sites have similar environmental settings (e.g. neutron intensity, soil chemistry), though different land covers with different amounts of biomass (stubble pasture and heathland).

At Voulund Farmland the ground level t/e ratio was measured to be 0.53 and 0.58 on September 22nd and September 23rd 2015, respectively. Only minor amounts of organic matter were present in the stubble and residual of spring barley harvested in August 2015. Additionally, the ground level t/e ratio was determined based on modeling of bare ground and site specific soil chemistry measured at Voulund Farmland (Andreasen et al., 2016). The modeled ratio was found to be 0.56 in agreement with the measured ratios. The ratio modeled based on the non-vegetated conceptualization of Gludsted Plantation was slightly higher (0.60, see Figures 16 and 17). Here, a 10 cm thick litter layer was included in the model. The sensitivity analysis on the effect of litter layer on neutron intensity (Figure 8 and Table 6) implies that lower ground level t/e ratios are found at locations with a thin or no litter layer.

The ground level t/e ratio at the Harrild Heathland was measured to 0.66 during the period October 27 to November 16 2015. The ratio is slightly higher than the non-vegetated model for Gludsted Plantation. Both field sites have a considerable layer of litter, and the slightly higher t/e ratio relative to the non-vegetated Gludsted Plantation may be due to biomass in the form of grasses, heather plants and bushes present at Harrild Heathland. At Gludsted Plantation, the ratio is 0.73 for dry above-ground biomass equivalent of 50 t/ha. Accordingly, the ratio measured at Harrild Heathland is somewhere in between the ratio modeled for a non-vegetated field site and a field site with biomass equivalent to 50 t/ha dry above-ground biomass.

The modeled decrease in ground level t/e ratios with smaller amounts of biomass are in line with the measurements conducted at the three field sites of similar soil chemistry and dissimilar land covers in terms of litter and vegetation.

Detecting the ground level t/e ratio at locations of known biomass should be accomplished to test the suggested relationship obtained using the forest canopy conceptualization of Model *Tree trunk, Foliage, Air*. We recommend a detection system with higher sensitivity to be used when a location of low neutron intensity rates (like Gludsted Plantation) is surveyed, unless long periods of measurements can be conducted at each measurement location. This can be accomplished by using larger sensors, an array of several sensors and/or sensors that are more efficient, as is done in roving surveys (Chrisman and Zreda, 2013; Franz et al., 2015).

4. Conclusion

The potential of applying the cosmic-ray neutron intensity method for other purposes than soil moisture detection was explored using profile and time-series measurements of neutron intensities combined with neutron transport modeling. The vegetation and subsurface layers of the forest model-setup were described by average measurements and estimates. Four forest canopy conceptualizations of increasing complexity were used. Without adjusting parameters and variables, modeled thermal and epithermal neutron intensity profiles compared fairly well with measurements, yet, some deviations from measurements were observed for each of the four forest canopy conceptualization models. The more appropriate forest canopy conceptualization was not obvious from the results as the best fit to thermal neutron measurements was found using complex forest canopy conceptualization, including a tree trunk and multiple materials, while the better fit to epithermal neutron measurements was found using the most simple forest canopy conceptualization, including a homogenous layer of foliage material. A sensitivity analysis was performed to quantify the effect of the forests governing parameters/variables on the neutron transport profiles. The sensitivity of canopy interception, dry bulk density of litter and mineral soil, and soil chemistry on neutron intensity was found to be small. The ground level t/e neutron ratio was found to increase with increasing amounts of canopy interception and to be independent of ground level thermal neutron intensity, ground level epithermal neutron intensity and soil moisture. However, the increase was minor and the measurement uncertainty exceeds the signal of canopy interception at a timescale appropriate to detect canopy interception at Gludsted Plantation (half-hour to hourly). However, the signal of canopy interception can potentially be isolated in measurements from locations of higher neutron intensities (lower latitudes and/or higher altitudes) with canopy interception of longer residence time and larger storage capacity (e.g. snow). Neutron intensity was found to be more sensitivity to litter layer, soil moisture and biomass at the forest field site. An increased litter layer at the forest floor resulted in reduced neutron intensities, particularly for epithermal neutrons. Forest biomass was found to alter the thermal and epithermal neutron transport significantly, both in terms of the shape of the neutron profiles and the t/e neutron ratios. The response to altered amounts of biomass on thermal and epithermal neutron intensity is non-unique for the simple and complex forest conceptualization and further advancement of the forest representation is therefore necessary. Still, both the difference between ground and canopy level thermal and epithermal neutron intensity, respectively, and the ground level t/e ratios were changed with additional amounts of biomass using the simple and complex forest canopy conceptualization. The best agreement between measurements and modeling was obtained for the ground level t/e neutron ratio using a model with a complex forest canopy conceptualization. Furthermore, the modeled ratios were found to agree well with two nearby field sites with different amounts of biomass (a bare ground agricultural field and a heathland field site).

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Tables

Table 1 – Dynamics of different hydrogen pools.

	Static	Quasi-static	Dynamic
Soil moisture			x
Tree roots		x	
Soil organic matter		x	
Water in soil minerals	x		
Vegetation (cellulose, water)		x	x
Snow		x	x
Puddles			x
Open water (river, sea, lake)		x	
Canopy intercepted water			x
Buildings/roads	x		
Atmospheric water vapor			x

Table 2 – Average tree height, tree diameter and dry bulk density (bd_{dry}) of the litter layer and the mineral soil at Gludsted Plantation field site. Tree height and diameter are representative of conditions for year 2012.

	Average	Standard deviation	Max.	Min.
Tree height* [m]	11	6	25	3
Tree diameter* [m]	0.14	0.08	0.34	0.03
Dry bulk density litter layer, [g cm^{-3}]	0.34	0.29	1.09	0.09
Dry bulk density mineral soil, [g cm^{-3}]	1.09	0.28	1.53	0.22

* Data obtained from the Danish Nature Agency

Table 3 – Chemical composition of major elements at Gludsted Plantation determined using X-ray fluorescence analysis on soil samples collected in 0.20-0.25 m depth.

	Gludsted Plantation [%]
O	52.78
Si	44.86
Al	1.54
K	0.53
Ti	0.29

Table 4 – Forest properties used in modeling.

*Specific for model with forest conceptualization of Model *Tree trunk*, *Foliage*, *Air*. **Reference model.

	Models				
	No vegetation	50 t ha^{-1}	100 t ha^{-1}**	200 t ha^{-1}	400 t ha^{-1}
Dry above-ground biomass [t ha^{-1}]	0	50	100	200	400
Wet above-ground biomass [t ha^{-1}]	0	91	182	364	727
Dry below-ground biomass [t ha^{-1}]	0	12.5	25	50	100
Wet below-ground biomass [t ha^{-1}]	0	23	45	91	182
Tree trunk density [g cm^{-3}] *	-	0.83	0.83	0.83	0.83
Tree trunk radius [m] *	-	0.07	0.07	0.07	0.07
Tree height [m] *	-	25	25	25	25
Foliage density [g cm^{-3}] *	-	0.00134	0.00151	0.00185	0.00255
Foliage band [m] *	-	2.44	1.70	1.18	0.82
Sub-cell size [m x m] *	-	6.67 x 6.67	4.72 x 4.72	3.34 x 3.34	2.36 x 2.36

Table 5 – Modeled ground level (1.5 m) and canopy level (27.5 m) thermal neutron intensity and epithermal neutron intensity for the Gludsted Plantation models including four different forest canopy conceptualizations (see Fig. 3).

		Thermal 1.5 m	Thermal 27.5 m	Epithermal 1.5 m	Epithermal 27.5 m
Gludsted Plantation models (Fig. 3)	Foliage	573	207	681	813
	Tree trunk, Air	484	272	610	695
	Tree trunk, Foliage	536	261	619	716
	Tree trunk, Air, Foliage	504	257	623	717

Table 6 – Sensitivity in modeled ground level (1.5 m) and canopy level (27.5 m) thermal neutron intensity and epithermal neutron intensity due to (1) soil moisture, (2) soil chemistry, (3) litter layer thickness, (4) mineral soil and litter dry bulk density (bd_{dry}), (5) canopy interception and (6) biomass. The sensitivity is provided in absolute values and are relative to the simulations based on Model *Tree trunk*, *Air*, *Foliage** and Model *Foliage***, respectively (see Fig. 3 and Table 5). Values provided in parentheses specifies the direct effect of one-by-one excluding soil organic matter (*third order complexity*), Gd (*second order complexity*), below ground biomass (*first order complexity*) and site specific major elements soil chemistry (SiO_2).

		Thermal 1.5 m	Thermal 27.5 m	Epithermal 1.5 m	Epithermal 27.5 m
Soil moisture models (Fig. 4)	0.18	504*	257*	623*	717*
	0.05	100	47	131	109
	0.10	45	20	58	50
	0.25	-25	-12	-27	-23
	0.35	-47	-22	-53	-45
	0.45	-59	-28	-69	-59
Soil moisture models (Fig. 5)	0.18	573**	207**	681**	813**
	0.05	119	40	142	115
	0.10	56	18	68	53
	0.25	-27	-9	-30	-23
	0.35	-50	-16	-55	-48
	0.45	-64	-21	-74	-61
Soil chemistry models (Fig. 6)	4^{th} order complexity	504*	257*	623*	717*
	3^{rd} order complexity	19 (+19)	8 (+8)	25 (+25)	14 (+14)

	2^{nd} order complexity	18 (-1)	9 (+1)	27 (-2)	17 (+3)
	1^{st} order complexity	22 (+4)	10 (+1)	26 (-1)	18 (+1)
	SiO_2	27 (+5)	11 (+1)	23 (-3)	19 (+1)
Litter layer models (Fig. 6A)	10.0 cm	504*	257*	623*	717*
	7.5 cm	11	4	26	22
	5.0 cm	18	9	53	41
	2.5 cm	24	12	85	71
	No litter layer	22	17	131	113
Density models	Gludsted Plantation*	504*	257*	623*	717*
	Higher litter layer bd_{dry}	-7	-5	-10	-6
	Higher mineral soil bd_{dry}	15	5	17	10
	Lower litter layer bd_{dry}	7	2	14	10
	Lower mineral soil bd_{dry}	-26	-13	-22	-18
Canopy interception models (Fig. 6B)	Dry canopy	504*	257*	623*	717*
	1 mm	4	-2	-3	0
	2 mm	7	-3	-5	5
	4 mm	15	-7	-5	2
Biomass models (Fig. 6C)	100 t ha^{-1}	504*	257*	623*	717*
	No vegetation	-67	-21	99	85
	50 t ha^{-1}	-16	-8	45	33
	200 t ha^{-1}	14	2	-70	-47
	400 t ha^{-1}	21	2	-172	-116
Biomass models (Fig. 6D)	100 t ha^{-1}	573**	207**	681**	813**
	No vegetation	-136	29	41	-28
	50 t ha^{-1}	0	24	13	-23
	200 t ha^{-1}	-9	-32	-26	22
	400 t ha^{-1}	-48	-59	-82	73

Figures

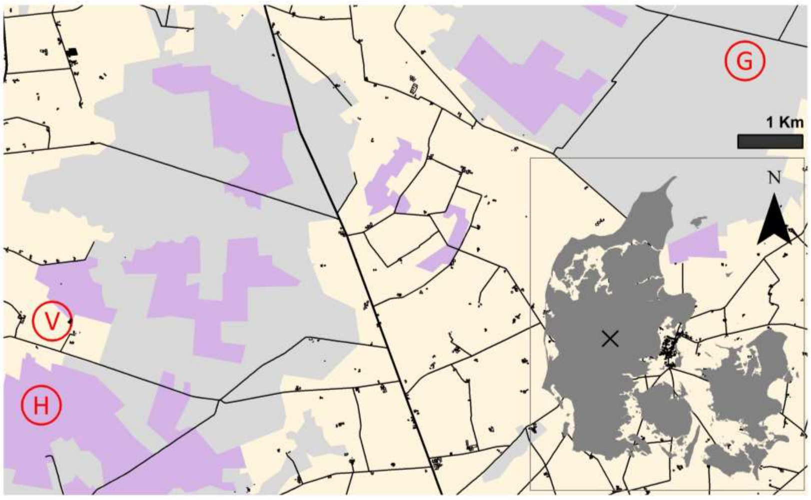

Figure 1 – Map showing the location of the three field sites; G: Gludsted Plantation (light gray), V: Voulund Farmland (beige) and H: Harrild Heathland (purple). The circles represent the footprint of the neutron detector (radius = 300 m).

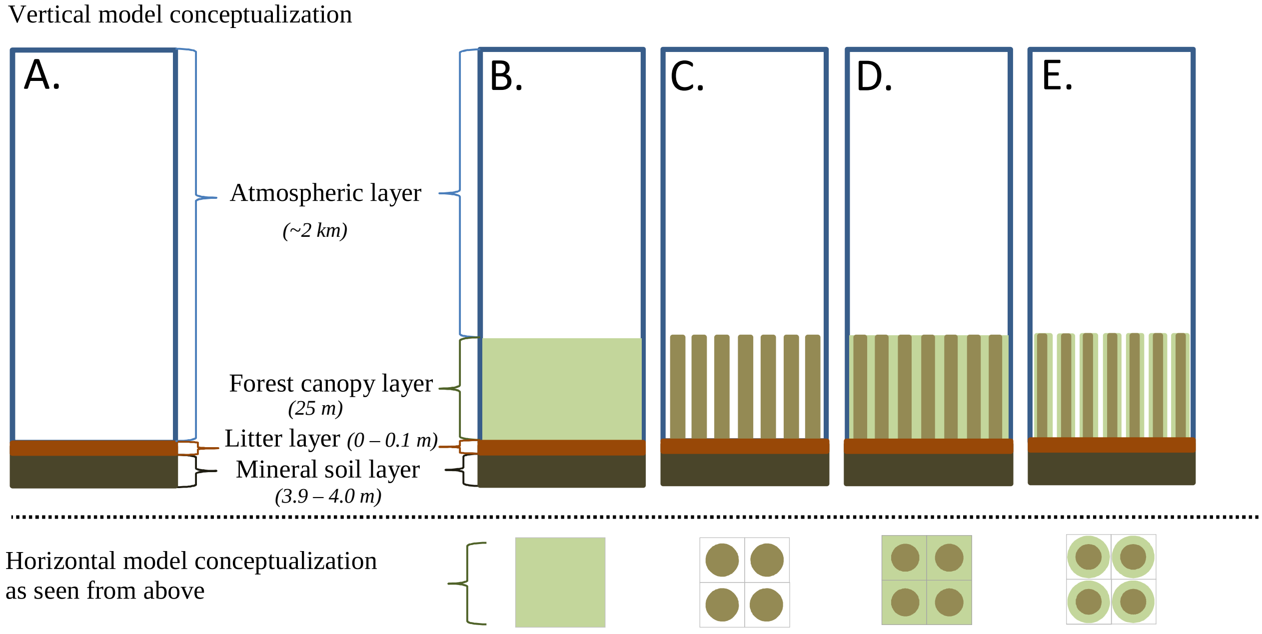

Figure 2 – Model conceptualizations of forest. A: no forest canopy layer (model name: *0 t ha*$^{-1}$); B: homogeneous foliage layer with a uniformly distributed biomass (model name: *Foliage*); C: cylindrical tree trunks with air in between (model name: *Tree trunks, Air*); D: cylindrical tree trunks with foliage in between (model name: *Tree Trunks, Foliage*); E: cylindrical tree trunks enveloped in a foliage-cover with air in between (model name: *Tree trunks, Foliage, Air*). The bottom four figures illustrate the forest conceptualization seen from above.

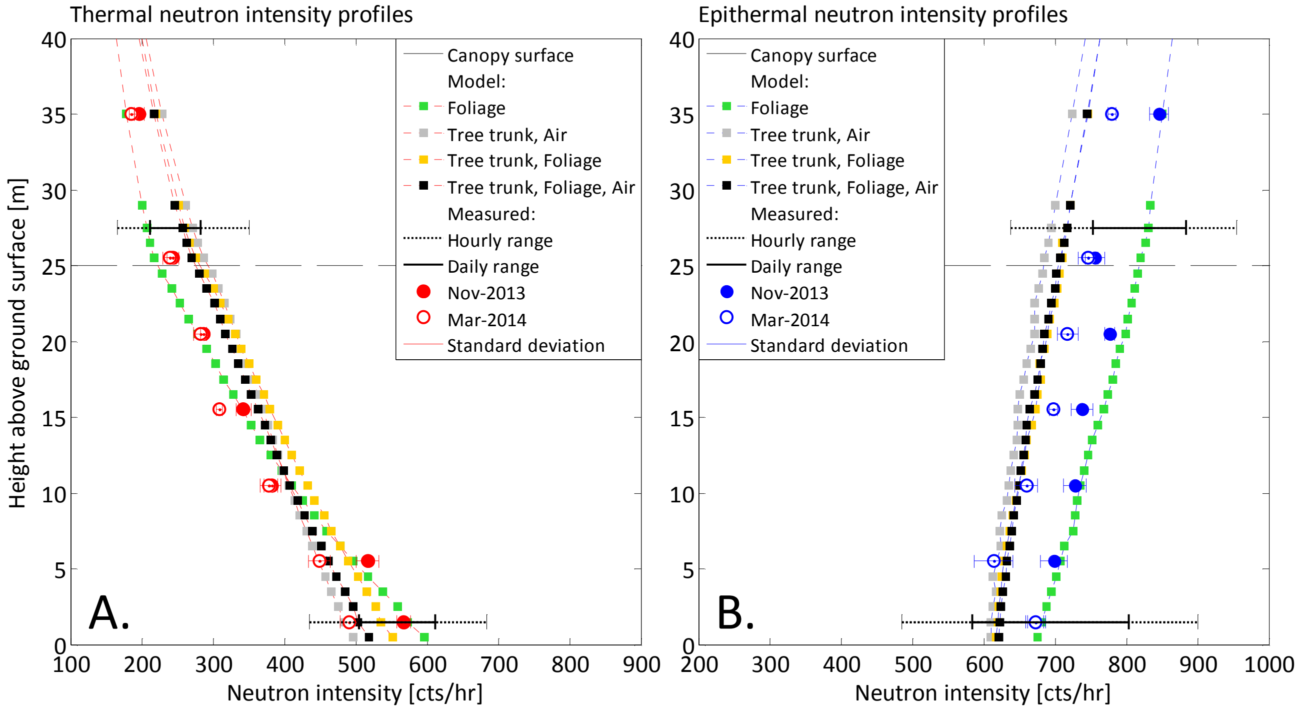

Figure 3 – Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015. Gludsted Plantation is modeled using four different forest canopy conceptualizations (see Figure 2).

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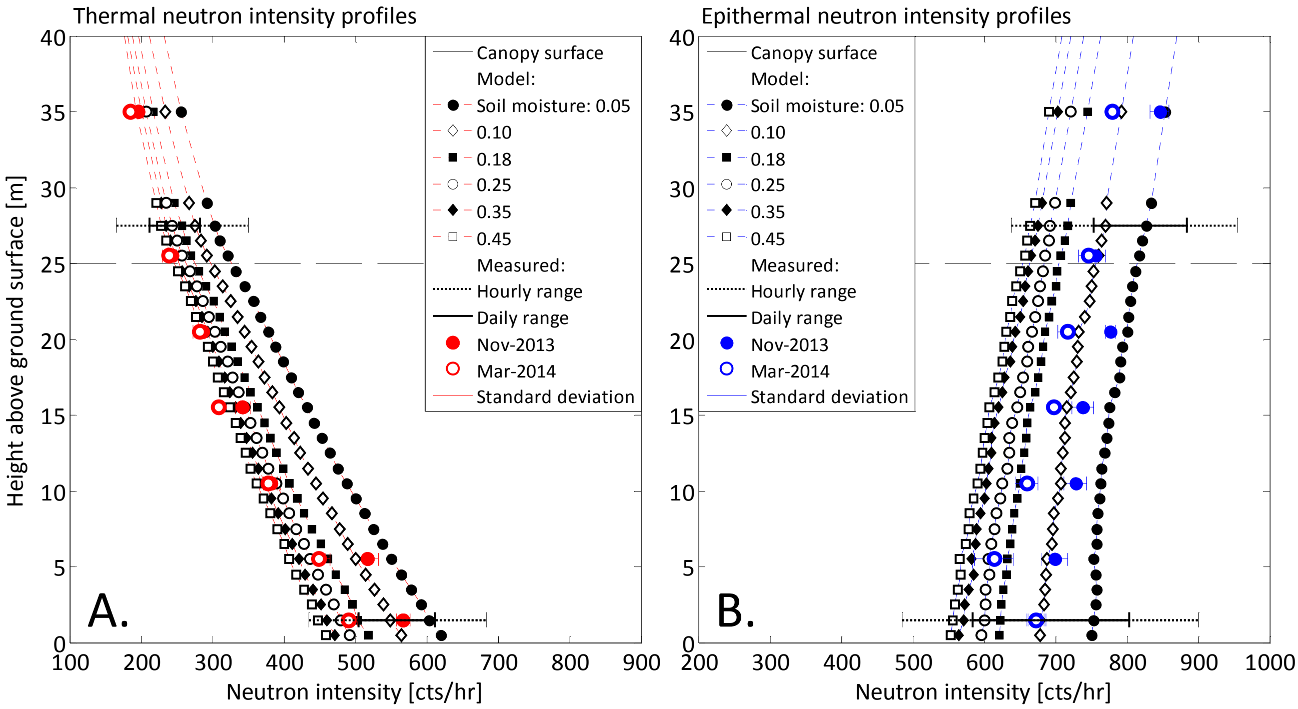

Figure 4 – Sensitivity to soil moisture (Model *Tree trunk*, *Foliage*, *Air*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.

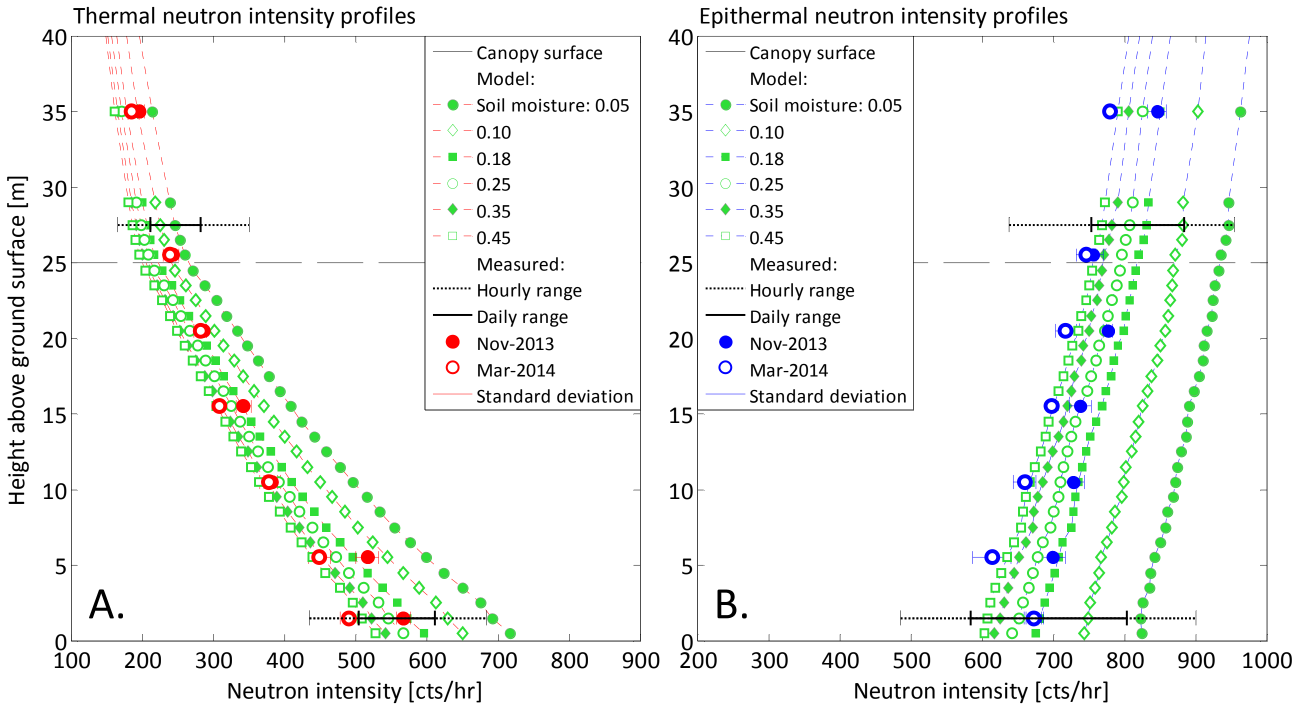

Figure 5 - Sensitivity to soil moisture (Model *Foliage*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.

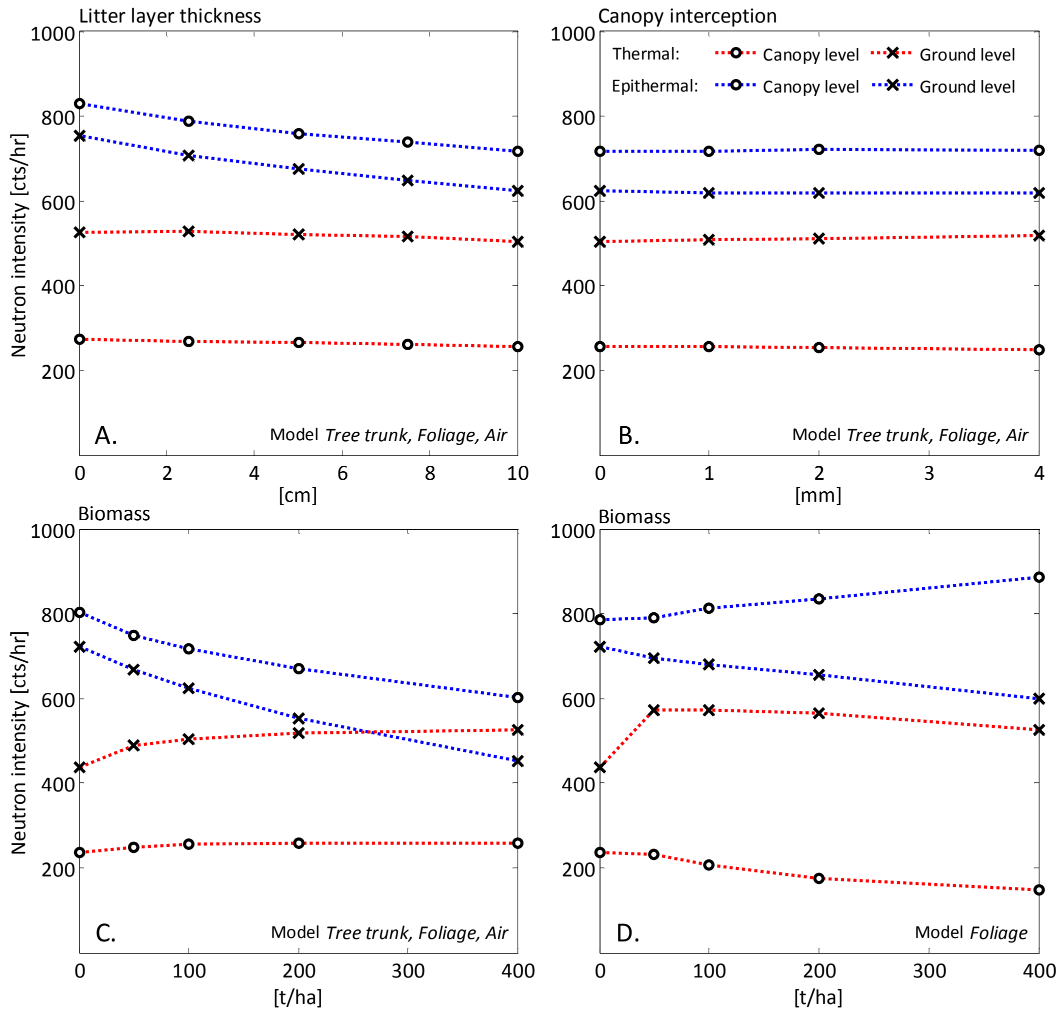

Figure 6 - Sensitivity to (A.) litter layer thickness using Model *Tree trunk*, *Foliage*, *Air*, (B.) canopy interception using Model *Tree trunk*, *Foliage*, *Air*, (C.) and D) biomass using Model *Tree trunk*, *Foliage*, *Air* and Model *Foliage*, respectively. Thermal and epithermal neutron intensity at ground and canopy level.

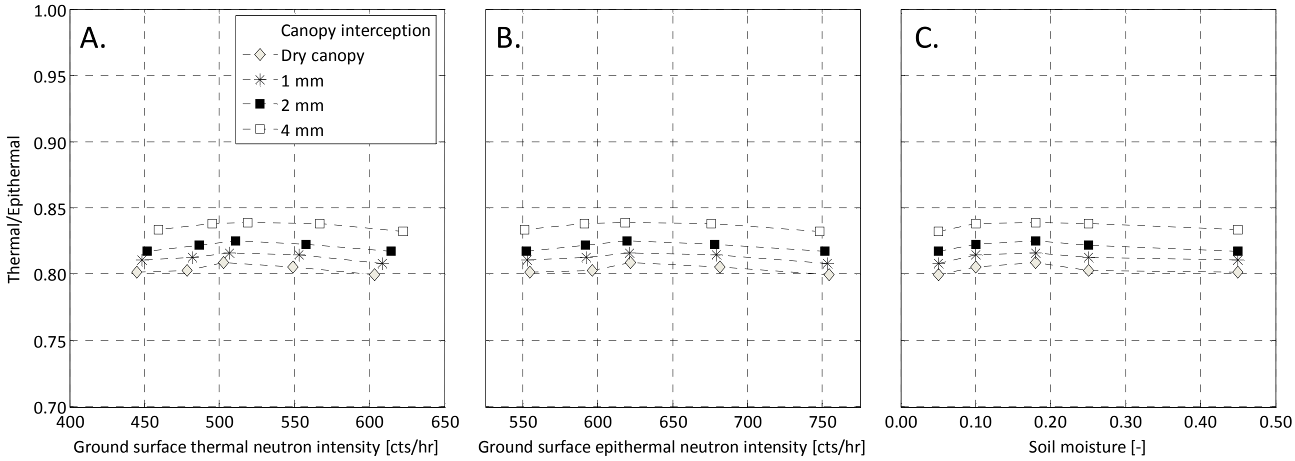

Figure 7 – Modeled ground level thermal-to-epithermal neutron intensity ratios using the Model *Tree trunk*, *Foliage*, *Air* for a dry forest canopy and canopy interception of 1 mm, 2 mm and 4 mm. plotted against modeled: A.) ground level thermal neutron intensity, B.) ground level epithermal neutron intensity, and C.) volumetric soil moisture.

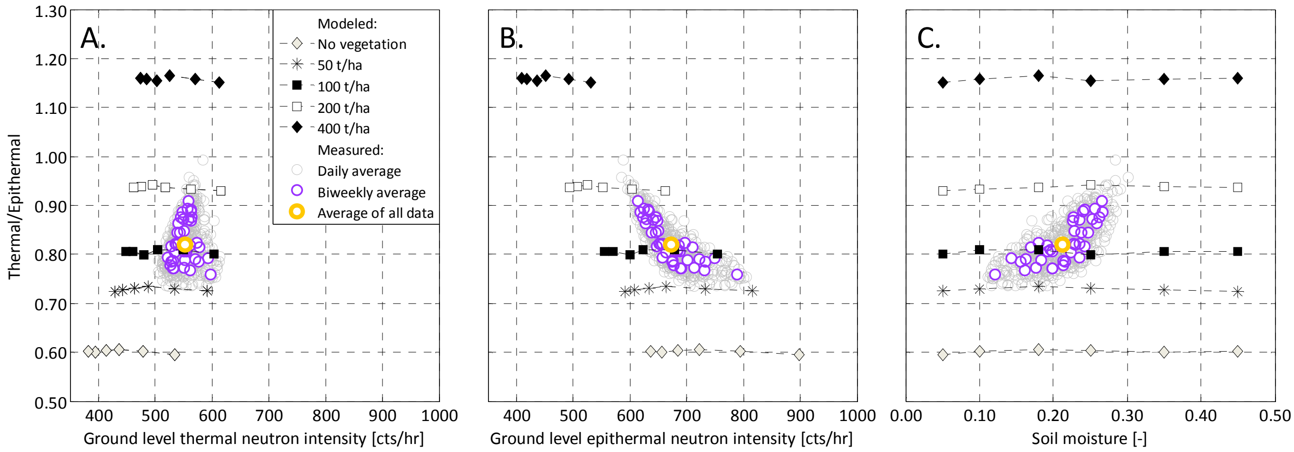

Figure 8 – Neutron intensities measured at Gludsted Plantation in the time period 2013-2015 and modeled using the Model *Tree trunk*, *Foliage*, *Air*. Ground level thermal-to-epithermal neutron intensity ratio plotted against measured and modeled: A.) ground level thermal neutron intensity, B.) ground level epithermal neutron intensity, and C.) volumetric soil moisture.

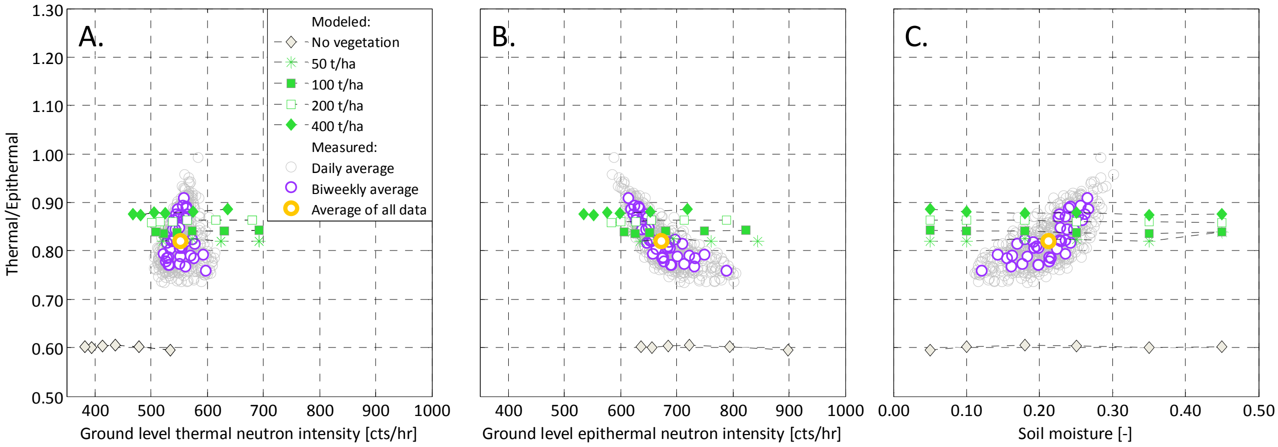

Figure 9 – Neutron intensities measured at Gludsted Plantation in the time period 2013-2015 and modeled using the Model *Foliage*. Ground level thermal-to-epithermal neutron intensity ratio plotted against measured and modeled: A.) ground level thermal neutron intensity, B.) ground level epithermal neutron intensity, and C.) volumetric soil moisture.

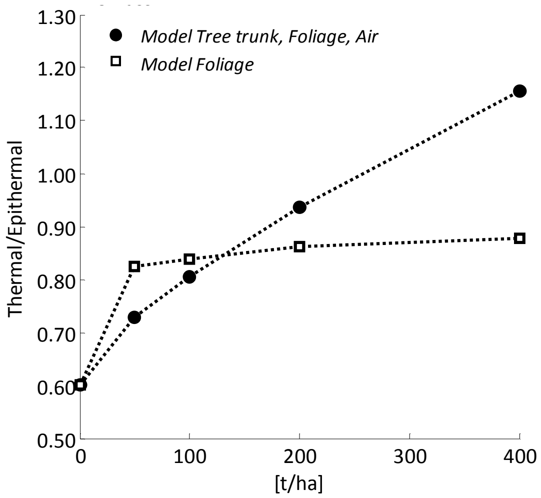

Figure 10 – Ground level thermal-to-epithermal neutron ratio plotted against biomass equivalent to dry above-ground biomass of: 50 t/ha, 100 t/ha (Gludsted Plantation), 200 t/ha and 400 t/ha using Model *Tree trunk, Foliage, Air* and Model *Foliage*, respectively.

~~Can canopy interception and biomass be inferred from cosmic~~Cosmic-ray neutron ~~intensity? Results from neutron~~ transport ~~modeling.~~at a forest field site: identifying the signature of biomass and canopy interception

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Keywords

1. Cosmic-ray neutron intensity method
2. Neutron transport modeling
3. Canopy interception
4. Forest biomass

Abstract

Cosmic-ray neutron intensity is inversely correlated to all hydrogen present in the upper decimeters of the subsurface and the first few hectometers of the atmosphere above the ground surface. This method has been used for measuring soil moisture ~~and snow water equivalent, but it may also be used to identify and quantify canopy interception and biomass.~~but several other hydrogen pools affect the signal. We use a neutron transport model with various representations of the forest and different parameters describing the subsurface to match measured height profiles and time series of thermal and epithermal neutron intensities at a field site in Denmark. A sensitivity analysis is performed to quantify the effect of ~~forest canopy representation,~~ soil moisture, complexity of soil matrix chemistry, forest litter, soil bulk density, canopy interception and forest biomass on ~~neutron intensity. The results show that forest biomass has a significant influence on the neutron intensity~~thermal and epithermal neutron intensities at multiple height levels above the ground surface. Overall, modeled thermal and epithermal neutron intensities are in satisfactory agreement with measurements, yet, the forest canopy conceptualization is found to be significant for the modeling results. The results show that the effect of canopy interception, soil chemistry and dry bulk density of litter and mineral soil on neutron intensity is small, while the sensitivity to litter layer thickness and biomass in addition to soil moisture is found to be significant. The neutron intensity decreases with added litter layer thickness, especially for epithermal neutron energies. Forest biomass has a significant influence on the neutron intensity height profiles at the examined field site, altering both the shape of the profiles and the ground level thermal-to-epithermal neutron ratio. ~~The ground level thermal-to-epithermal neutron~~The ratio increases significantly with increasing amounts of biomass and ~~minor~~insignificantly with canopy interception. Satisfactory agreement is found between measurements and model estimates of biomass results at the forest site as well as two nearby sites representing agricultural and heathland ecosystems. The measured ground level thermal-to-epithermal neutron ratios of the three ~~site~~sites range from around 0.56 to 0.82. ~~The~~A significantly smaller effect of canopy interception on the ground level thermal-to-epithermal neutron ratio was modeled to range from 0.~~804~~80 to 0.~~836~~84 for a forest with a dry and a very wet canopy (4 mm of canopy interception), respectively. ~~At the examined field site the signal of the canopy interception is lower than the measurement uncertainty.~~

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1. Introduction

~~The cosmic-ray neutron intensity (eV range) at the ground surface is a product of the elemental composition and density of the immediate air and soil matrix. Hydrogen is, because of its physical properties and often relative high concentration, a significant element controlling neutron transport. As a result, neutron intensity is inversely correlated with the hydrogen content of the surrounding hectometers of air and top decimeters of the ground (Zreda et al., 2008). Neutron intensity~~

measurements were found to be suitable for the detection of soil moisture since it often forms the major dynamic pool of hydrogen within the footprint of the detector. Soil moisture plays an important role in water and energy exchanges at the ground-atmosphere interface, but is difficult and expensive to measure at the intermediate scale. (hectometers). The cosmic-ray method has been developed to circumvent the shortcomings of existing measurement procedures for soil moisture detection at the multi hectare scale (e.g. Zreda et al. (2008) and Franz et al. (2012)). The cosmic-ray neutron intensity (eV range) at the ground surface is a product of the elemental composition and density of the immediate air and soil matrix. Hydrogen is, because of its physical properties and often relatively high concentration close to the land surface, a significant element controlling neutron transport. As a result, neutron intensity is inversely correlated with the hydrogen content of the surrounding hectometers of air and top decimeters of the ground (Zreda et al., 2008). Neutron intensity measurements were found to be suitable for the detection of soil moisture since it often forms the major dynamic pool of hydrogen within the footprint of the detector.

Cosmic-ray neutron intensity detection also has potential for estimating other pools of hydrogen present within the footprint of the neutron detector (Zreda et al., 2008; Desilets et al., 2010). Hydrogen is stored statically, quasi-statically or dynamically in soil water, atmospheric water vapor, in water in soil minerals, soil organic matter, snow, and buildings/roads, quasi-statically in above and below ground biomass, soil organic matter, snow and lakes/streams, or dynamically in soil water, atmospheric water vapor and canopy intercepted precipitation (see Table 1). The signal of some of these hydrogen pools has already been investigated with the aim of correcting cosmic-ray neutron soil moisture measurements. A scheme to correct the fast neutron signal for time-varying atmospheric water vapor was developed by Rosolem et al. (2013) using neutron transport modeling; and a correction function was determined to account for above-ground biomass based on field measurements (Baatz et al., 2015). Until now independent measurements of neutrons impacted by hydrogen pools other than soil moisture have received little attention.

Table 1 is inserted here

The ability to separate signals of canopy interception and biomass from To date, studies have primarily aimed to advance the cosmic-ray neutron soil moisture estimation method by determining correction models to remove the effect of other influencing pools of hydrogen.

Rosolem et al. (2013) examined the effect of atmospheric water vapor on the neutron intensity (10-100 eV; 1 eV = $1.6*10^{-19}$ J) using neutron transport modeling and determined a scheme to rescale the measured neutron intensity to reference conditions. For the preparation of cosmic-ray neutron data correction for changes in atmospheric water vapor is along with corrections for temporal variations in barometric pressure and incoming cosmic radiation a standard procedure (Zreda et al., 2012).

Most studies have focused on improving the N_0 calibration parameter used for soil moisture estimation at forest field sites but also at high-yielding crop field sites like maize. Bogena et al. (2013) demonstrated the importance of including the litter layer in the calibration for cosmic-ray neutron soil moisture estimation at field locations with a significant litter layer. The

N_0 calibration parameter obtained from field measurements was found to decrease with increasing biomass (Rivera Villarreyes et al., 2013; Hornbuckle et al., 2012; Hawdon et al., 2014; Baatz et al., 2015). wouldIn order to account for this effect Baatz et al. (2015a) defined a correction model to remove the effect of biomass on the neutron intensity signal. A different approach was presented by Franz et al. (2013b). Here a universal calibration function was proposed where separate estimates of the various hydrogen pools are included for cosmic-ray neutron soil moisture estimation.

Few studies have explored the potential of using the cosmic-ray neutron method for additional applications. Desilets et al. (2010) distinguished snow and rain events using measurements of two neutron energy bands, and Sigouin and Si (2016) reported an inverse relationship between snow water equivalent and the neutron intensity measured using the moderated detector. Franz et al. (2013a) demonstrated an approach to isolate the effect of vegetation on the neutron intensity signal and estimate area average biomass water equivalent in agreement with independent measurements. Finally, the signals of biomass and canopy interception on neutron intensity, measured using the moderated detector, have also been investigated by Baroni and Oswald (2015). They account the higher soil moisture estimated using the cosmic-ray neutron method compared to the up-scaled soil moisture measured at point-scale to be the impact of canopy interception and biomass. The two pools of hydrogen were then separated in accordance to their dynamics.

The ability to separate the signals of the different hydrogen pools on the neutron intensity is valuable both for the advancement of the cosmic-ray neutron soil moisture estimation method and for the potential of additional applications. The potential of determining canopy interception and biomass from the cosmic-ray neutron intensity is valuable as they form essential hydrological and ecological variables. Both are difficult and expensive to measure continuously at larger scales. Although the unwanted effect of biomass and biomass growth on cosmic-ray estimated soil moisture (Hornbuckle et al., 2012)neutron intensity can potentially be accounted for using independent methods (thereby improving soil moisture determinations),, there is currently no established method for independently constraining biomass based on cosmic-ray neutron data alone.

Canopy interception is for some climatic and environmental settings an important variable to include in water balance studies, as well as in hydrological and climatological modeling. For the forest site studied here the canopy interception loss was found to be 31-34% of the gross precipitation, making it a vital variable to consider (Ringgaard et al., 2014). A common method to estimate canopy interception is by subtracting the precipitation measured at ground level below canopy (throughfall) from precipitation measured above the forest canopy (gross precipitation) using standard precipitation gauges. TheHowever, the spatial scale of measurement is small and is not representative of larger areas as the canopy interception is highly heterogeneous. In order to obtain a representative measure of canopy interception multiple throughfall stations must be installed. This is labor intensive and measurement uncertainties are significant. Precipitation underestimation due to wind turbulence, wetting loss, and forest debris plugging the measurement gauge at the forest floor are sources of significant uncertainty (Dunkerley, 2000).

The forest biomass represents an important resource for timber industry and renewable energy. Furthermore, forest modifies the weather through the mechanisms and feedbacks related to evapotranspiration, surface albedo and roughness. Overall, the forest ecosystems have a cooling impact on global climate as significant amounts of carbon are accumulated through photosynthesis. Carbon sequestration by afforestation and an effective forest management is a widely used method to decrease the concentration of carbon dioxide in the atmosphere and thereby attenuate the greenhouse effect (Lal, 2008). The carbon sequestration in vegetation can be quantified by monitoring the growth of biomass over time. The most conventional and accurate method to estimate forest biomass is the use of allometric models describing the relationship between the biomass of a specific tree species and easily measurable tree parameters, such as tree height and tree diameter at breast height (Jenkins et al., 2003). However, this approach is time consuming and labor intensive because numerous trees have to be surveyed to obtain accurate and representative results (Popescu, 2007). Remote sensing technology offers alternative methods to estimate biomass as high correlations are found between spectral bands and vegetation parameters. One method providing high resolution maps is airborne *Light Detection And Ranging* (LiDAR) technology (Boudreau et al., 2008). The LiDAR system is installed in small aircrafts and digitizes the first and last return of near-infrared laser recordings. The canopy height at a decimeter grid-size scale can be obtained and the biomass can be estimated from regression models. Instruments and aircraft-surveys are expensive, and measurements of tree growth will often be at a coarse temporal resolution.

~~Here,~~Previous studies examining the ~~potential~~effect of ~~detecting intermediate scale canopy interception and biomass from~~ hydrogen on cosmic-ray neutron ~~intensities is investigated. The analysis is based on~~intensity has for most cases considered a single neutron energy range (neutron intensity measured using the moderated neutron detector) at a single height level (typically 1.5 m above the ground). Thermal and epithermal neutrons are both sensitive to hydrogen, but are characterized by very different physical properties resulting in unique responses to environmental settings and conditions at the immediate ground-atmosphere interface. For this reason, thermal and epithermal neutron intensity ~~profiles of~~at multiple height levels above the ground surface are considered in this study.

The study is conducted at a forest ~~boundary layer~~field site using thermal and epithermal neutron measurements from ~~proportional detectors and modeling. Thermal and epithermal neutron intensity measurements are obtained from measurements using~~ bare and moderated detectors constrained with correction factor models (Andreasen et al., 2016~~).~~ ~~Modeling is based on~~) and modeling using the recognized and widely used ~~neutron~~ Monte Carlo N-Particle transport ~~model MCNP6~~code (MCNP) (Pelowitz, 2013).

Neutron transport modeling of specific sites is limited and has only been performed for non-vegetated field sites (Franz et al., ~~2013~~2013b; Andreasen et al., 2016). In this context, forest sites are especially complex to conceptualize as the number of free parameters is ~~very~~relatively high (e.g. biomass, litter, soil chemistry, interception and the structure of the forest). ~~In this study~~Here, we first focus on modeling a ~~sensitivity analysis of various forest canopy conceptualization model setups, forest parameters and variables to identify and quantify their effect on modelled thermal and epithermal neutron intensity at forest sites.~~

~~The effects are identified and quantified in relation to a reference model of the~~ forest field site. ~~This~~The model is developed from measured soil and vegetation parameters at the specific locality. The modeled neutron intensity profiles are evaluated against profile measurements on two different dates separated by five months, and also against time-series of neutron intensity measurements at two heights. Specifically, we test the possibility to isolate and quantify the signals from canopy interception and biomass. In addition, measurementsFollowing, the forests environmental impact on thermal and epithermal neutron intensities are identified and quantified by applying a sensitivity analysis based on the model representative of the forest field site. In addition to improving the understanding of the environmental effect on neutron transport the focus is also on examining the potential of detecting intermediate scale canopy interception and biomass from cosmic-ray neutrons. Measurements at an agricultural field site with no biomass and at a heather field site with a smaller amount of biomass are used to underpin the assessment.influence of certain environmental variables (e.g., biomass, litter layer). To our knowledge this is the first study which provides a quantitative analysis of the potential of using the cosmic ray technique for estimation of interception and biomass.

2. Field locations

Three field sites are used in this study; the primary site is Gludsted Plantation, and two secondary sites are Voulund Farmland and Harrild Heathland. The sites are located within Skjern River Catchment in the Western part of Denmark (Figure 1) and are all part of the Danish hydrological observatory (HOBE) (Jensen and Illangasekare, 2011). The sites are situated at an elevation of approximately 50 - 60 m above sea level on an outwash plain from the last glaciation composed of nutrient depleted sandy stratified soils. Harrild Heathland is located 1 km south of Voulund Farmland, both approximately 10 km west of Gludsted Plantation.

Figure 1 is inserted here

Gludsted Plantation forest field site (56°04'24"N 9°20'06"E) is situated within a coniferous forest plantation covering an area of around 3500 ha. The trees of the plantation are densely planted in rows and are in general composed of Norway spruce with small patches of Sitka spruce, Larch and Douglas fir. Within the field site area (38 ha) the trees were estimated to be up to 25 m high and the dry above-ground biomass to be around 100±46 t/ha (one standard deviation) using LiDAR images from 2006 and 2007 (Nord-Larsen and Schumacher, 2012). The dry below-ground biomass was calculated to be 25 t/ha using a root-to-shoot ratio for Norway spruce of 0.25 (Levy et al., 2004). Information on the vegetation at the forest field site is acquired from a register managed by The Danish Nature Agency (representative of the 2012 conditions); see Table 2.

Table 2 is inserted here

In Scandinavian forests around 79% of the total above-ground biomass of Norway spruce is stored within the tree trunks. The remaining 21% is found in the branches and needles (termed *foliage*). A typical density of the tree trunk is 0.83 g/cm^3 (Serup et al., 2002). The major component of the tree biomass is cellulose ($C_6H_{10}O_5$) and represents around 55% of the total mass, while the remaining 45% is vegetation water (Serup et al., 2002). Based on these approximations, the wet above- and below-ground biomass at the field site area are estimated to be 182 t/ha and 45 t/ha, respectively. With a leaf area index

(LAI) of 4.5 and a canopy interception capacity coefficient of 0.5 mm/LAI (Andreasen et al., 2013) the maximum storage of canopy intercepted rain is estimated to be 2.25 mm.

Soil samples were collected within the footprint of the cosmic-ray neutron detector on August 26 – 27, 2013 following the procedure of Franz et al. (2012). Based on these samples the organic rich litter layer is found to be 5 - 10 cm thick. The dry bulk density of the litter and mineral layer are calculated by oven drying the soil samples (Table 2), and the soil organic matter content of the mineral soil is determined from the loss-on-ignition method (16.9% in 10 - 20 cm depth and 7.6% in 20 – 30 cm depth). A time series of soil moisture is calculated from cosmic-ray neutron intensity, starting in spring, 2013, using the N_0-method as presented in Desilets et al. (2010). Lastly, the chemical composition of the soil matrix is estimated for two random soil samples collected at 20-25 cm depth using the *X-ray fluorescence* (XRF) analysis (Table 3).

Table 3 is inserted here

The element Gadolinium (Gd) can have a significant impact on thermal neutron intensity even at low concentrations due to its very high absorption cross-section of 49000 barns (1 barn = 10^{-24} cm^2). The detection limit of the XRF in this study is 50 ppm for gadolinium (Gd). The two soil samples from Gludsted Plantation both have Gd concentration below the detection limit of the XRF. Inductively coupled plasma mass spectrometry (ICP-MS) detects metals and several non-metals at very small concentrations and was used to characterize the soil chemistry of a nearby field site with similar soil conditions (Salminen et al., 2005). A Gd concentration of 0.51 ppm was found at that site and we assume this value to be representative of the conditions at Gludsted Plantation.

Gludsted Plantation is a heavily equipped research field site with a 38-m high tower for measurements at multiple heights within the forest canopy. The tower is instrumented with an eddy-covariance system, humidity and air temperature sensors in addition to other sensors not used in this study (Ringgaard et al., 2011). Precipitation is measured using a tipping bucket mounted on top of an instrument container. Additionally, throughfall is measured using tipping buckets at three locations within the cosmic-ray neutron detector footprint. Four 6-m long rain gutters were placed in four directions from the tipping bucket, providing a surface area of 2.5 m^2.

Voulund Farmland (56°02'14"N 9°09'38"E) is an agricultural field site. In 2015, the fields were cropped with spring barley. After harvest in the late summer until ploughing in spring 2016 (prior to sowing) the fields were covered with stubble (around 10 cm high). A 25 cm layer of relatively organic rich soil (4.45% soil organic matter) is found at the top of the soil column and is a result of the cultivation practices. More information about the field site can be found in Andreasen et al. (2016).

Harrild Heathland (56°01'33"N 9°09'29"E) is a shrub land field site dominated by grasses and heather. The heathland is maintained by controlled burning, yet, the field site area has not recently been burnt. An organic rich litter layer of around 10 cm thickness is present at the top of the mineral soil and is observed visually during soil sampling field campaigns at the field site. Podsolization has resulted in a low permeability hardpan-layer at a depth of around 25-30 cm hindering percolation.

~~3.~~2. Method

~~3.1.~~2.1. Terminology

The energy of a neutron determines the probability of the neutron interacting with other elements and the type of interaction (i.e. absorbing or scattering). Overall, an important threshold for the behavior of low energy neutrons is present at energies somewhere below 0.5 eV ~~(1 eV = 1.6*10^{-19} J).~~. The specific energy ranges of thermal, epithermal and fast neutrons are ambiguous. The following terminology for neutron energies is used for the purpose of this paper:

- Thermal: Energy range 0 – 0.5 eV.
- Epithermal: Energies above 0.5 eV.
- Fast: Energy range 10 - 1000 eV.

When modeling neutron transport for hydrological applications it is common to consider fast energy ranges (10 – 100 eV or 10 – 1000 ~~ev~~eV) (Desilets et al., 2010; 2013; Rosolem et al., 2013; Franz et al., ~~2013~~2013b; Köhli et al., 2015), while measurements using standard soil moisture neutron detectors ~~will at best represent~~is sensitive to the entire epithermal energy range (Andreasen et al., 2016). ~~Despite this fact, we will use~~Here, the term epithermal neutrons will be used for both measured neutrons of energies above 0.5 eV and modeled ~~energy ranges.~~ neutrons of energies 10 – 1000 eV.

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~~3.2.~~2.2. Cosmic-ray neutron detection

~~3.2.1.~~2.2.1. Equipment

Cosmic-ray neutron intensity was measured using the CR1000/B system from Hydroinnova LLC, Albuquerque, New Mexico. The system has two detectors that consist of tubes filled with boron-10 (enriched to 96%) trifluoride ($^{10}BF_3$) proportional gas. The neutron detection relies on the $^{10}B(n,\alpha)^{7}Li$ reaction for converting thermal neutrons into charged particles (α) and then into an electronic signal. One detector is unshielded (bare detector), while the other is shielded by 25 mm of high-density polyethylene (moderated detector). These different configurations give the bare and moderated tubes different energy sensitivities.

The thermal neutron absorption cross-section of ^{10}B is very high (3835 barns) (Sears et al., 1992). This absorption cross-section decreases rapidly with increasing neutron energy following a $1/E_n^{0.5}$ law (where E_n is neutron energy) (Knoll 2010). Therefore, the energies measured by the bare tube comprise a continuous distribution which is heavily weighted toward thermal neutrons (<0.5 eV), with a small proportion of epithermal neutrons also being detected (<10%) (Andreasen et al., 2016).

The moderated detector is more sensitive to higher neutron energies (> 0.5 eV). The purpose of the polyethylene is to slow (moderate) epithermal neutrons through interactions with hydrogen in order to increase the probability of them being captured by ^{10}B in the detector. At the same time the polyethylene attenuates the thermal neutron flux through neutron capture by hydrogen. Nonetheless, a large proportion (approximately 40% of the thermal neutrons detected by the bare detector) originates from below 0.5 eV (Andreasen et al., 2016).

Obeying Poissonian statistics (Knoll 2010) the measurement uncertainty of a given neutron intensity, N, decreases with increasing neutron intensity and the standard deviation equals $N^{0.5}$.

The measured neutron intensities are corrected for variations in barometric pressure, atmospheric water vapor and incoming cosmic-ray intensity following procedures of Zreda et al. (2012) and Rosolem et al. (2013). Unfortunately, the water vapor correction of Rosolem et al. (2013) is only valid for~~ fast and~~ epithermal neutron measurements. Since the development of correction methods is beyond the scope of this study, we refrained from using a vapor correction for the measured thermal neutron intensities. We believe that this missing correction will only have a minor effect on our results~~.~~ (Andreasen et al., 2016). Nevertheless, we suggest that future studies should investigate the effect of water vapor on thermal neutron intensities and to develop appropriate correction methods.

~~3.2.2.~~2.2.2. Pure thermal and epithermal neutron detection

We expect thermal and epithermal neutrons to have unique responses to environmental properties and settings. Therefore, it is important to consider pure signals of thermal and epithermal neutrons, and not simply the raw neutron intensity signal measured by the bare and moderated detectors. In order to limit the epithermal and thermal neutron contribution to the bare and the moderated detectors, respectively, we use the cadmium-difference method (Knoll, 2010; Glasstone and Edlund, 1952). The thermal absorption cross-section of cadmium is very high (approximately 3500 barns) for neutron energies below 0.5 eV. The cross-section drops to approximately 6.5 barns at neutron energy 0.5 eV and remains low with increasing neutron energies. Thus, a cadmium shielded neutron detector only measures neutrons of energies higher than 0.5 eV. The epithermal neutron intensity was measured from a cadmium shielded moderated detector, while the thermal neutron intensity was calculated by subtracting the neutron intensity measured by the cadmium-shielded bare detector from the neutron intensity measured by the bare detector (unshielded). The cadmium-difference method is described in Andreasen et al. (2016) in detail.

Appropriate neutron energy correction~~ factor~~ models were applied in order to obtain pure thermal and pure epithermal neutron intensity measurements for the time periods when the cadmium-difference method was not applied (Andreasen et al., 2016). The neutron energy correction ~~factors~~models were obtained from field campaigns applying the cadmium-difference method on bare and moderated detectors at various locations (height levels and land covers). The determination of the neutron energy correction models was based on the relationships of measurements from unshielded and shielded neutron detectors (Andreasen et al., 2016).

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~~3.2.3.~~2.2.3. Footprint

~~The footprint of the two detectors is not expected to be the same as the properties of thermal and epithermal neutrons are very different.~~ The footprint of the bare detector is unexplained, while the footprint of the moderated detector was determined from modeling by Desilets and Zreda (2013) and Köhli et al. (2015). However the findings of these two studies were inconsistent. Desilets and Zreda (2013) used the neutron transport code Monte Carlo N-Particle eXtended (MCNPx) and found the footprint to be nearly 600 m in diameter in dry air, while Köhli et al. (2015) using the Ultra Rapid Adaptable Neutron-Only Simulation (URANOS) estimated the footprint to be 260 – 480 m in diameter depending on the air humidity, soil moisture and vegetation. The potential mismatch in the footprint of the bare and the moderated detectors is a concern when combining the neutron intensity measurements. In this study we will as a first approximation assume that neutron intensities measured by the two different detector types can be compared asNevertheless, the environmental conditions at the field sites are fairly homogeneous and although the footprint might be different as a first approximation we assume the neutron intensity measured using the bare and the moderated detector are comparable.

3.2.4.2.2.4. Field measurements

Three field sites are used in this study; the primary site is Gludsted Plantation, and two secondary sites are Voulund Farmland and Harrild Heathland. The sites located within the Skjern River Catchment in the Western part of Denmark represents the three major land use types (Figure 1) and are all part of the Danish hydrological observatory (HOBE) (Jensen and Illangasekare, 2011). The sites are situated at an elevation of approximately 50 - 60 m above sea level on an outwash plain from the last glaciation composed of nutrient depleted sandy stratified soils. Harrild Heathland is located 1 km south of Voulund Farmland, both approximately 10 km west of Gludsted Plantation.

Figure 1 is inserted here

Gludsted Plantation forest field site (56°04'24"N 9°20'06"E) is situated within a coniferous forest plantation covering an area of around 3500 ha. The trees of the plantation are densely planted in rows and are in general composed of Norway spruce with small patches of Sitka spruce, Larch and Douglas fir. Within the field site area (38 ha) the trees were estimated to be up to 25 m high and the dry above-ground biomass to be around 100±46 t/ha (one standard deviation) using LiDAR images from 2006 and 2007 (Nord-Larsen and Schumacher, 2012). The dry below-ground biomass was calculated to be 25 t/ha using a root-to-shoot ratio (the weight of the roots to the weight of the aerial part of the tree) for Norway spruce of 0.25 (Levy et al., 2004). Information on the vegetation at the forest field site (e.g. tree species, ages, heights and trunk diameters) is acquired from a register managed by The Danish Nature Agency (representative of the 2012 conditions); see Table 2.

Table 2 is inserted here

In Scandinavian forests around 79% of the total above-ground biomass of Norway spruce is stored within the tree trunks. The remaining 21% is found in the branches and needles (termed *foliage*). A typical density of the tree trunk is 0.83 g/cm^3 (Serup et al., 2002). The major component of the tree biomass is cellulose ($C_6H_{10}O_5$) and represents around 55% of the total mass, while the remaining 45% is vegetation water (Serup et al., 2002). Based on these approximations, the wet above- and below-ground biomass at the field site area are estimated to be 182 t/ha and 45 t/ha, respectively. With a leaf area index (LAI) of 4.5 and a canopy interception capacity coefficient of 0.5 mm/LAI (Andreasen et al., 2013) the maximum storage of canopy intercepted rain is estimated to be 2.25 mm.

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Gludsted Plantation is a heavily equipped research field site with a 38-m high tower for measurements at multiple heights within the forest canopy. At Gludsted Plantation, CR1000/B systems were installed at ground level (1.5 m height) and canopy level (27.5 m height) in the spring of 2013. Hourly neutron intensities have been continuously detected (Andreasen et al., 2016) except for short periods where the detectors were used for other types of measurements or during times of malfunctions. Neutron intensity profiles extending from the ground surface to 35-m-height above the ground were measured at approximately 5 m-increments during two field campaigns on November 28 – 29, 2013 and March 12 - 14, 2014 at Gludsted Plantation. ~~During~~In order to obtain comparability between measurements and modeling pure thermal and epithermal neutron signals were estimated using neutron energy correction models on measurements from bare and moderated detectors, respectively. The neutron energy correction models were both used on time-series and neutron height profile measurements. Additionally, during the field campaign on March 12 -14, 2014 an epithermal neutron intensity profile (with no thermal contribution) was measured using a cadmium-shielded moderated detector (Andreasen et al., 2016). For the profile measurements neutron intensities were recorded at a 10-minute time resolution. As the thermal neutron intensity decreases significantly with height we choose to extend the time of measurement with the height level increments to maintain a low and consistent measurement uncertainty. The volumetric soil moisture content measured using the cosmic-ray neutron method (Zreda et al., 2008) was 0.18 during both field campaigns.

Voulund Farmland (56°02'14"N 9°09'38"E) is an agricultural field site. In 2015, the fields were cropped with spring barley. After harvest in the late summer until ploughing in spring 2016 (prior to sowing) the fields were covered with stubble (around 10 cm high). A 25 cm layer of relatively organic rich soil (4.45% soil organic matter) is found at the top of the soil column and is a result of the cultivation practices. More information about the field site can be found in Andreasen et al. (2016). Ground level neutron intensities were measured on September 22 and 23, 2015 at Voulund Farmland (Andreasen et al., 2016). The measurements were conducted using the bare and the moderated neutron detectors normally installed at

Gludsted Plantation and data were logged every 10 minutes. In order to obtain pure thermal and epithermal neutron height profiles the neutron energy correction models were applied.

Harrild Heathland (56°01'33"N 9°09'29"E) is a shrub land field site dominated by grasses and heather. The heathland is maintained by controlled burning, yet, the field site area has not recently been burnt. The organic rich litter layer is found to be around 10 cm thick during soil sampling field campaigns at the field site. Due to podsolization a low permeable hardpan-layer hindering percolation to deeper depths is present at around 25-30 cm depth. In the period from October 27 to November 16, 2015 the ground level thermal and epithermal neutron intensity was measured directly at Harrild Heathland using the cadmium-difference method (Knoll, 2010). The cadmium-difference method was applied using two bare and one moderated detector normally installed at Gludsted Plantation. The neutron intensity was integrated and recorded on an hourly basis. ~~The measurements at Voulund Farmland and Harrild Heathland will be used in the discussion of the effect of biomass and litter on thermal and epithermal neutron intensity.~~

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~~3.3.~~2.3. Neutron transport modeling

The three-dimensional Monte Carlo N-Particle transport code version 6 (MCNP6) (Pelowitz, 2013) simulating thermal and epithermal neutrons is used to model the forest field site. The code holds libraries of measured absorption and scattering cross-sections used to compute the probability of interactions between earth elements and neutrons. The MCNP6 combines Monte Carlo N-Particle Transport code version 5 (MCNP5) and Monte Carlo N-Particle Extended Radiation Transport code (MCNPX). MCNPX has been used for most neutron transport modeling within the field of hydrology (Desilets et al., 2013; Rosolem et al., 2013; Zweck et al., 2013). However, the improved and more advanced MCNP6 has recently been introduced and provided more realistic neutron intensity profiles for Voulund Farmland field site (Andreasen et al., 2016).

The number of particle histories released at the center of the upper boundary of the model domain is specified to obtain an uncertainty below 1%. The released particles represent a distribution of high-energy particles typical for the spectrum of incoming cosmic-rays traveling through the atmosphere. The modeled neutron intensities are normalized per unit source particle providing relative values (Zweck et al., 2013). In order to obtain values comparable to measurements conversion factors are used (Andreasen et al., 2016). The conversion factors 3.739×10^{12} and 1.601×10^{13} are multiplied by the modeled thermal neutron fluences in the energy range of 0 – 0.5 eV and epithermal neutron fluences in the energy range 10 – 1000 eV, respectively. We stress that, the conversion factors are detector-specific as well as dependent on the horizontal area of the model~~-~~-setup in MCNP6. The dependence of the environmental settings is at this point in time unclear and should be addressed in future studies.

~~3.3.1.~~2.3.1. The Gludsted Plantation reference model

The model domain of MCNP6 is defined by cells of varying geometry, and each cell is assigned a specific chemical composition and density. The lowest 4 m of the Gludsted Plantation reference model consists of subsurface layers. The chemical composition of the mineral soil is prescribed according to the chemical composition from XRF measurements; assumed Gd concentration of 0.51 ppm, wet below-ground biomass (cellulose) of 45 t/ha, dry bulk density of 1.09 g/cm^3 and soil moisture content of 0.18. The litter layer is defined according to the chemical composition of cellulose, dry bulk density of 0.34 g/cm^3 and moisture content similar to that of mineral soil (see also Table 3). The same soil moisture was used for the whole soil column, as the soil moisture profile was unknown for the days of neutron profile measurements, and furthermore we wanted to test the signal of soil moisture. The atmosphere is composed of 79% nitrogen and 21% oxygen by volume and extends from the forest canopy surface to the upper boundary of the model domain at approximately 2 km height. Here, an incoming spectrum adapted to the specific level of the atmosphere is specified (Hughes and Marsden, 1966). The density of air is assumed to be 0.001165 g/cm^3. Multiple sublayers of varying vertical discretization cover the vertical extent of the model in order to record neutron intensities at multiple heights and depths from the ground surface. The resolution of the layers increases with proximity to the ground surface ranging in thickness from 0.025 m to 0.20 m for the subsurface layers and from 1 m to 164 m for the layers above the ground surface. 1 m layers are used from the ground to 28 m height to enable neutron intensity to be modeled at the measured heights. The neutron intensity detectors are layers of 1 m height and extent the full lateral model domain (400 m x 400 m). Reflecting surfaces constrain the model domain. Thus, the particles reaching a model boundary will be reflected specularly back into the model domain. Wet above-ground biomass of 182 t/ha is distributed within the forest canopy layers extending from the ground surface to 25 m above the ground (Table 4).

The proper way to conceptualize the forest canopy in the model-setup is not obvious and the sensitivity to forest representation on neutron intensity is therefore investigated using four model-setups of increasing complexity. In the first representation (Model *Foliage*; Figure 2B) the same material composed of cellulose and air (foliage) is assigned all forest canopy layers. In order to obtain a wet above-ground biomass of 182 t/ha a relatively low density of 0.00189 g/cm^3 is calculated for the material. In order to allow for a forest canopy layer to be composed of multiple materials (cellulose and air) and densities (massive tree trunks and less dense foliage and air), the horizontal discretization of the forest canopy layers is reduced to smaller cells ~~of 4.72 m by 4.72 m (Figure 2E).~~

~~Table 4 and Figure 2 are inserted here~~

for the next tree model-setups. The bole of each tree is for all three model-setups represented by a cylinder with a diameter of 0.14 m, a composition of cellulose, and a density of 0.83 g/cm^3. A tree is placed at the center of each cell and extends from the ground surface to the top of the forest canopy layer~~ and foliage is specified as a 1.7 m thick band around the tree cylinder. The foliage material is a composite of air and cellulose and the density is the sum of the two (0.00151 g/cm^3). The remaining volume of the cells is composed of air. A total of 7182 trees are evenly spaced within the model domain.~~. In the second representation (Model *Tree trunk, Air*; Figure 2C) the horizontal discretization of the forest canopy layers is set to~~As previously described, the share of biomass stored in the tree trunk and the foliage is 79% and 21%, respectively, typical of Norway spruce.~~

~~3.3.2.1.1.1. Sensitivity to environmental conditions~~

~~The sensitivity of neutron intensity to forest representation is investigated by comparing the results of the reference model (Figure 2E) with the results of three alternative representations of the forest canopy (Figures 2B-D). In the first representation (Model *Foliage*; Figure 2B) the forest canopy layers is not reduced to smaller cells as a homogeneous layer~~

with a relatively low density material composed of cellulose and air was used to describe the forest. Here, the total density of cellulose and air is 0.00189 g/cm^3. In the second representation a smaller horizontal discretization of the forest canopy layers is implemented (Model *Tree trunk, Air*; Figure 2C). The setup is similar to the reference model except for the cell size and the materials included describing the forest canopy layers. Here, the cells are 4.20 m by 4.20 m and the remaining volume beyond the bole of the tree is made of air alone (density 0.001165 g/cm^3). ForThus, for this model all biomass is stored in the bole of the trees and the cell size is adjusted to obtain a wet above-ground biomass of 182 t/ha resulting in 9070 trees within the model domain. In the third representation the setup is equal to the reference model except that air is not included in the description of the forest canopy layers (Model *Tree trunk, Foliage*; Figure 2D). Here, the cell is divided between) the horizontal discretization of the forest canopy layers is 4.72 m by 4.72 m and the remaining volume beyond the bole of the tree andis made of foliage. As previously described, the share of biomass stored in the tree trunk and the foliage is 79% and 21%, respectively, typical of Norway spruce. The foliage material is composeda composite of cellulose and air, and the total density of the material is the sum of the two (0.001318 g/cm^3.). A total of 7182 trees are evenly spaced within the model domain. The density of the foliage in fourth and most complex forest canopy conceptualization (Model *Tree trunk, Foliage*; Figure 2E) is smaller than forequal to the reference model asModel *Tree trunk, Foliage* except that air is also included in the volumedescription of the foliage is largerforest canopy layers and the density of the foliage is reducedincreased to obtain the same above-ground biomass as for the other models. The foliage is specified as a 1.7 m thick band around the tree cylinder and the density of foliage material composted of air and cellulose is 0.00151 g/cm^3.

Table 4 and Figure 2 are inserted here

2.3.2. Sensitivity to environmental conditions

The reference model is used to test the sensitivity of the modeled thermal and epithermal neutron intensities to soil moisture. is examined using modeling. The soil moisture in the Gludsted Plantation reference model is specified to 0.18 and both drier and wetter soils are modeled to test the sensitivity, i.e. 0.05, 0.10, 0.25, 0.35 and 0.45. The same soil moisture range is modeled usingBoth the Model *Foliage*forest canopy conceptualization of Model *Tree trunk, Foliage, Air* and the Model *Foliage* are used.

In addition to hydrogen theThe thermal and epithermal neutron intensity is alsoboth a product of thehydrogen abundance as well as elemental composition and density of the soil matrix. The. The Gludsted Plantation reference model including a complex forest conceptualization (Model *Tree trunk, Foliage, Air)* is used to test the sensitivity of the modeled thermal and epithermal neutron intensities to soil chemistry. The Gludsted Plantation reference model holds the most complex soil chemistry (*fourth order complexity*) with multiple subsurface layers composed of measured concentrations of major elements determined by XRF, soil organic matter, gadolinium and roots (Table 3). One component is excluded at a timeIn order to test the effect of simplifying the soil chemistry a component is excluded one at the time: 1) *third order complexity*; soil organic matter is excluded, 2) *second order complexity*; soil organic matter and roots are excluded, 3) *first order complexity*; soil organic matter, roots and gadolinium are excluded, and 4) *pure SiO_2*; all other components are excluded.

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The sensitivity of the modeled thermal and epithermal neutron intensities to the presence of the organic litter layer is investigated using the Gludsted Plantation reference model, including a complex forest conceptualization (Model *Tree trunk, Foliage, Air),* in which the thickness of the litter layer is set to be 10.0 cm. Sensitivity simulations are carried out for the following thicknesses of the litter layer: 0.0 cm, 2.5 cm, 5.0 cm and 7.5 cm. For all litter layer models, the total thickness of the subsurface is kept constant at 4 m.

The materials of forest floor litter and mineral soil differ distinctly in terms of chemical composition and dry bulk density. The determination of dry bulk density of the two materials is characterized by measurement uncertainty, especially for the litter as sampling and drying is very challenging for materials including large amounts of soil organic matter (O'Kelly, 2004). Given that the elemental composition and density of the soil matrix is relevant for the neutron intensity the sensitivity of dry bulk density on thermal and epithermal neutron intensity is examined. The dry bulk density of the Gludsted Plantation reference model is set to 0.34 g/cm^3 for the litter layer and 1.09 g/cm^3 for the mineral soil. The Gludsted Plantation reference model including the complex forest conceptualization (Model *Tree trunk, Foliage, Air)* is used to test the sensitivity applying four scenarios: 1) higher dry bulk density of the litter layer (0.50 g/cm^3), 2) higher dry bulk density of the mineral soil (1.60 g/cm^3), 3) lower dry bulk density of the litter layer (0.20 g/cm^3), and 4) lower dry bulk density of the mineral soil (0.60 g/cm^3). All values with the exception of higher dry bulk density of 1.60 g/cm^3 for the mineral soil (standard value for quartz; soil particle density of 2.66 g/cm^3 and a porosity of 0.40) are within the range of the measurements (see Table 2).

The Gludsted Plantation reference model including the complex forest conceptualization (Model *Tree trunk, Foliage, Air)* is used to test the sensitivity to canopy interception by increasing the density and water content of the cells described by foliage material. The forest canopy of the reference model is dry (foliage material density 0.00151 g/cm^3). In order to test the effect, water equivalent to 1 mm (foliage material density 0.00155 g/cm^3), 2 mm (foliage material density 0.00159 g/cm^3) and 4 mm (foliage material density 0.00167 g/cm^3) of canopy interception is added to the foliage volume.

The sensitivity to biomass is investigated using the Gludsted Plantation reference model with the complex forest conceptualization (Model *Tree trunk, Foliage, Air*) ~~as well as a~~and the simplified model-setup (Model *Foliage*). The biomass of the Gludsted Plantation reference model is equivalent to a dry above-ground biomass of 100 t/ha and a dry below-ground biomass of 25 t/ha, following the root-to-shoot ratio of 0.25 typical of Norway spruce. This distribution is used for both ~~models~~model setups. For the sensitivity analysis one model without vegetation (Model *0 t/ha*, Figure 2A) and three models with different amounts of biomass are used (see Table 4). The forest canopy layer extending uniformly from the ground to 25 m above the ground surface is for the model with no vegetation assigned with the material composition and density of air. The amount of biomass modeled for the three remaining models is equivalent to a dry above-ground biomass of: 1) 50 t/ha, 2) 200 t/ha, and 3) 400 t/ha. The size of the cells in the forest layers and the density of the foliage material are adjusted in order to obtain the correct amount of biomass.

4.3. Results and discussions

3.1. Gludsted Plantation

4.1. The reference

Neutronneutron intensity profiles for Gludsted Plantation are modeled with the Gludsted Plantation referenceusing four different forest canopy conceptualizations. The model results are presented in Fig. 3, along with time-series of hourly and daily ranges of thermal and epithermal neutron intensities collected at the Gludsted Plantation during the period 2013-2015, and measured/estimated thermal and epithermal neutron intensity profiles (November 2013 and March 2014). Following the Poissonian statistics the relative uncertainty decreases with increasing neutron intensity. The relative measurement uncertainty is therefore lowerhigher for the hourly time series data than for the multi-hourly (2-12 hr) and daily measurements. AllAccordingly, we choose to rely mostly on the time-series measurements are included in all, as the measurement uncertainty is lower than for the neutron profile figures, i.e. Figs. 4 – 12, to enable comparisonheight profiles.

Figure 3 is inserted here

We choose to rely mostly on the Overall, time-series and profile measurements, as provide similar results in agreement with theory. The thermal neutron intensity decreases considerable with height above ground surface and is at canopy level reduced by around 50% compared to at the ground level. The epithermal neutron intensity increases slightly with height and is around 10-15% higher at the neutron canopy level compared to the ground level. Still, some differences are observed between the neutron height profiles are very different despite of similar measured in November 2013 and March 2014. The soil moisture was similar during the time of neutron profile detection. The different neutron profiles may and we expected the differences to be a result of different climate and weather conditions related to the seasons of detections (spring and fall). Furthermore, although the area average soil moisture is the same for the two field campaigns the soil moisture profiles may be different resulting in different neutron profile slopes and thermal-to-epithermal neutron (t/e) ratios. In particular, the assumption of identical soil moisture of the litter layer and the mineral soil may be inappropriate as this was not the case during two out of three soil sampling field campaigns where the results differed considerably (soil samples were collected at 18 locations within a circle of 200 m in radius and in 6 depths from 0-30 cm depth following the procedure of Franz et al. (2012)). However, both neutron profiles are within the ranges of the daily time-series measurements and we therefore still believe that they can be used in the assessment of the modeled neutron profiles. For future studies we recommend soil sample field campaigns to be conducted on the days of neutron profile measurements.

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AOverall, a remarkable agreement between measured and modeled neutron intensities is seen in Fig. 3. We stress that no calibration of the governing physical properties in the forest model is performed and that the estimates are based on measured properties. The modeled thermal neutron intensity profiles are especially consistent with measurements, as both modeled ground and canopy neutron intensity are within the daily measurement ranges. In contrast, the modeled epithermal neutron profile isThe ground and canopy level thermal and epithermal neutron intensity for the four forest canopy conceptualization models are provided in Table 5. slightly underestimated and the profile slope is steeper than the measured profiles. Nevertheless, the modeled epithermal neutron intensity profile is still within the ranges of the time-series of hourly measurements at both height levels. To investigate whether the slight misfit of measurements and modeling may be due to misrepresentations in litter and mineral soil layer thickness, density and composition, forest canopy conceptualization, canopy interception and soil moisture a sensitivity analysis of these parameters and variables is conducted.

4.2. Forest conceptualization

The thermal and epithermal neutron intensity profiles modeled using the Gludsted Plantation reference model (Model *Tree trunk, Foliage, Air*) and three models with other forest canopy conceptualizations are presented in Fig. 4.

Figure 4 is inserted here

All modeled neutron intensity profiles are within the range of hourly time-series measurements, and in particular the thermal neutron profiles are in agreement with measurements. Overall, the models of the more complex forest canopy conceptualizations, including a tree trunk, provide similar thermal and epithermal neutron profiles. modeled satisfactorily. The ground and canopy level thermal neutron intensity of models with forest canopy conceptualization of Model *Tree trunk, Foliage* and Model *Tree trunk, Foliage, Air* are within the daily ranges of the time-series measurements. In contrast, the modeled epithermal neutron profiles of the more complex models are slightly underestimated and the profile slope is steeper than the measured profiles. Nevertheless, the modeled epithermal neutron intensity profile is still within the ranges of the time-series of hourly measurements at both height levels. Overall, the models of the more complex forest canopy conceptualizations, including a tree trunk, provide similar thermal and epithermal neutron profiles. The neutron intensity profiles of the simpler forest canopy conceptualization of Model *Foliage* is less steep and is the only model providing an epithermal neutron intensity profile within the daily ranges of the time-series measurements at both the ground and canopy level.

The sensitivity of forest canopy conceptualization on thermal and epithermal neutron intensities is quantified at the ground and canopy level relative to the reference model (Table 5).

Table 5 is inserted here

The most appropriate forest canopy conceptualization is not obvious from Fig. 4 and Table 53 as the best fit of the thermal measurements is found using a complex conceptualization, while the more simple foliage conceptualization matches the epithermal measurements better. We can, however, conclude that the neutron transport at the ground-atmosphere interface is highly sensitive to the level of complexity of the forest canopy conceptualization. ForImproved comparability to measurements may be obtained by advancing the following analysis the most complex model was chosen for the sensitivity analysis, although some examples of modeling using the simplest forest canopy conceptualization will be provided.. Currently, one tree is defined and repeated throughout the model domain. The trees are placed in even rows and the same settings are applied from the ground surface to 25 m height. In order to advance the forest canopy conceptualization, trees of different heights and diameters could be included, and the placement of the trees could be more according to the actual placement of trees at the forest field site. Additionally, variability in tree trunk diameter, foliage density and volume with height above the ground surface could be implemented.

Here, a sensitivity analysis is perform using the most complex model and occasionally the simplest forest canopy conceptualization to examine the effect of soil moisture, soil dry bulk density and composition, litter and mineral soil layer thickness, canopy interception and biomass on the thermal and epithermal neutron transport at the immediate ground-atmosphere interface.

3.2. Soil moisture

The modeled thermal and epithermal neutron intensity profiles of the Gludsted Plantation *reference model*Model *Tree trunk, Foliage, Air* and Model *Foliage* using six different soil moistures, 0.05, 0.10, 0.18, 0.25, 0.35 and 0.45, are presented in Figs. 5 and 6, respectively. 4 and 5, respectively. To enable comparison the measurements included in Fig. 3 are also included in Figs. 4 and 5. The sensitivity of soil moisture on thermal and epithermal neutron intensities at the ground and canopy level relative to the Model *Tree trunk, Foliage, Air* and Model *Foliage* at reference conditions (soil moisture 0.18) is provided in Table 6.

Figure 5 and4, Figure 5 and Table 6 are inserted here

As expected, the thermal and epithermal neutron intensity is seen in Table 6, Figs. 54 and 65 to decrease with increasing soil moisture. For both model-setups, the largest changes in neutron intensity occur at the dry end of the soil moisture range and for the epithermal neutrons (see also Table 5).. For the reference modelModel *Tree trunk, Foliage, Air* (Figure 54), only a minor decrease in the sensitivity of soil moisture on epithermal neutron intensity is observed going from ground level to canopy level (approximately 15% reduction in intensity range corresponding to a soil moisture change of 0.40). On the other hand, the sensitivity of the thermal neutron intensity is reduced more than 50% (Table 56) most likely caused by the lower mean-free path length of the thermal neutrons compared to that of epithermal neutrons. The response to soil moisture is similar for the model with a simple forest canopy conceptualization (Figure 65). However, both thermal and epithermal neutron intensities are found to be slightly more sensitivity to soil moisture. Neutron intensity at dry and wet soil conditions is represented by the range of time-series neutron intensity measurements. Overall, the modeled neutron intensities are within the measurement range and the more appropriate model-setup for Gludsted Plantation is not obvious from the modeling results.

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4.3.3.3. Subsurface properties

Thermal and epithermal neutron intensity profiles are modeled using the reference modelModel *Tree trunk, Foliage, Air* (with *fourth order complexity*) and models of decreasingly complex soil chemistry are presented in Fig. 7.

Figure 7 is inserted here

The effect of varying . Soil organic matter, below-ground biomass, Gd and the chemical composition from XRF measurements are excluded one at the time (from *third* to *first order complexity*) and the final model includes a simple silica soil ~~chemistry on thermal and epithermal neutron intensity profiles is small at Gludsted Plantation.~~(*SiO*$_2$). The exact sensitivity of excluding the different components ~~(soil organic matter, gadolinium, roots and major elements relative to a simple soil chemistry of SiO$_2$)~~ on ground and canopy level thermal and epithermal neutron intensity is quantified in Table ~~5~~6 (see values in parentheses). Only the removal of soil organic matter (*third order complexity*) changes the neutron intensity significantly at Gludsted Plantation, i.e. an increase in the ground level thermal and epithermal neutron intensity of 19 cts/hr (cts = counts) and 25 cts/hr, respectively, is observed. The sensitivity to soil chemistry on thermal and epithermal neutron intensity profiles was found to be ~~much~~ more substantial at Voulund Farmland (Andreasen et al., 2016). The soil organic matter content at Voulund Farmland is smaller and the soil chemistry is, except from a few elements (added in relation to farming activities; spreading of manure and agricultural lime), similar to Gludsted Plantation. Modelling shows that the sensitivity to soil chemistry at Gludsted Plantation is dampened by the considerable amount of hydrogen present in the forest biomass and the litter at the forest floor (not presented here).

~~In Fig. 8, the~~The thermal and epithermal neutron intensity ~~profiles~~is modeled for a forest with litter layer of various thicknesses ~~are presented. The Gludsted Plantation reference model with~~(Figure 6A). The Model *Tree trunk, Foliage, Air* including a 10.0 cm thick litter layer is used along with forest models with litter layers of 0.0 cm, 2.5 cm, 5.0 cm and 7.5 cm thickness.

Figure ~~8~~6 is inserted here

Neutron intensities are found to decrease with an increasing layer of litter, having the greatest impact on the epithermal neutron intensities~~.~~ (see also Table 6). The considerable amount of hydrogen in litter causes the probability of scattering of neutrons travelling through the subsurface to increase with increasing amounts of litter. Thereby, the ~~thermal-to-epithermal neutron intensity ratio~~t/e is found to be altered when changing the thickness of the litter layer. This effect is most pronounced when the model without a litter layer is compared to the model with just a thin 2.5 cm thick litter layer~~ (see also Table 5).~~

~~Thermal and epithermal neutron intensity profiles modeled using the Gludsted Plantation reference model and models of altered bulk densities of subsurface layers are provided in Fig. 9.~~

~~***Figure 9 is inserted here***~~

~~The modified bulk densities of litter and mineral soil~~. Additionally, the sensitivity to litter and mineral soils dry bulk density on neutron intensity is examined as a considerable range of values is measured within the footprint of the neutron detector (see Table 2). Models including higher litter layer (0.50 g cm^{-3}) and mineral soil dry bulk density (1.60 g cm^{-3}) as well as lower litter layer (0.20 g cm^{-3}) and mineral soil dry bulk density (0.60 g cm^{-3}) only provided slight changes in thermal and epithermal neutron intensities. Nevertheless, a reverse response of changed bulk densities is observed. A decrease in neutron intensity is obtained both by increasing the dry bulk density of the litter material and decreasing the dry bulk density of the mineral soil. Conversely, higher neutron intensities are computed by decreasing the ~~bulk density of the litter material and~~

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increasing the bulk density of the mineral soil. Thus, heredry bulk density of the litter material and increasing the dry bulk density of the mineral soil. The production rate of low-energy neutrons (<1 MeV) per incident high-energy neutron is higher for interactions with elements of higher atomic mass ($A^{2/3}$, where A is the atomic mass) (Zreda et al., 2012). Heavier elements are in particular found in mineral soil and an increase in the dry bulk density entails a higher production rate and therefore higher neutron intensity. The concentration of hydrogen is increased with an increased dry bulk density of litter material resulting in a greater moderation and absorption of neutrons, and as a consequence lower neutron intensities. To summarize, the mineral soil acts as a producer of thermal and epithermal neutrons, while the litter acts as an absorber.

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4.4.3.4. Canopy interception

TheThe effect of canopy interception on thermal and epithermal neutron intensity profilesis modeled by the Gludsted Plantation reference model with a dry forest canopy (model: *Dry canopy*) and models of 1 mm, 2 mm and 4 mm of canopy interception are presented in Fig. 10.

using Model *Tree trunk, Foliage, Air* (Figure ***10 is inserted here***

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6B and Table 6). Except for a slight increase in ground level thermal neutron intensities with wetting of the forest canopy, no effect of canopy interception on ground and canopy level thermal and epithermal neutron intensity is observed in Fig. 10. A maximum change of approximately 3% (15 cts/hr) is observed for thermal neutron intensity at ground level going from a dry canopy to 4 mm of canopy interception. At the specific field site a maximum canopy storage capacity of 2.25 mm is expected, producing a change in observed ground level thermal neutron intensity of approximately 7 cts/hr. Given an average neutron intensity of 504 cts/hr of ground level thermal neutrons with the installed detectors, an uncertainty of 22 cts/hr is expected based solely on Poissonian statistics. In order to obtain a signal-to-noise ratio of 1, either an 11-hour-integration time or 11 detectors similar to the installed are needed. However, longer integration times are not appropriate when considering Gludsted Plantation as the return time of canopy interception (cycling between precipitation and evaporation) often is short (half-hourly to hourly time resolution).

Although detection of canopy interception at Gludsted Plantation is unfavorable it may still be possible at more appropriate locationsconditions. Canopy interception modeling as described above is therefore also performed for soil moisture 0.05, 0.10, 0.25 and 0.40. Ground level thermal-to-epithermal neutron ratiost/e ratio of the 20 model combinations are plotted against ground level thermal neutron intensity, ground level epithermal neutron intensity and volumetric soil moisture (Figure 117). We choose not to include measurementmeasurements in the figure as we from the calculation in the previous section foundbecause the measurement uncertainty at a relevant integration time to beis greater than the signal of canopy interception.

Figure 7 is inserted here

Figure 11 is inserted here

Overall, ground level ~~thermal-to-epithermal neutron~~t/e ratio is found to be independent of ground level thermal neutron intensity (Figure ~~11A~~7A), ground level epithermal neutron intensity (Figure ~~11B~~7B) and volumetric soil moisture (Figure ~~11C~~7C). Ground level ~~thermal-to-epithermal neutron~~t/e ratio is found to increase with increasing canopy interception. The ground level ~~thermal-to-epithermal neutron~~t/e ratio for a dry canopy is on average 0.804, while the average at 4 mm of canopy interception is 0.836. Overall, the same increase in ground level ~~thermal-to-epithermal neutron~~t/e ratio is obtained per 1 mm additional canopy interception. Although the change in the t/e ratio with wetting/drying of the forest canopy is small the canopy interception may potentially be measured using cosmic-ray neutron intensity detectors at locations with: 1) a high neutron intensity level (lower latitude and/or higher altitude, 2) more sensitive neutron detectors, and 3) greater amounts of canopy interception with longer residence time (e.g. snow). We suggest future studies investigating the effect of canopy interception on the neutron intensity signal to be performed at locations matching one or more of these criteria.

~~4.5.~~3.5. **Biomass**

The sensitivity to the amount of forest biomass on thermal and epithermal neutron intensity ~~profiles~~ using the forest canopy conceptualization of Model *Tree trunk, Foliage, Air* ~~(reference model)~~ and Model *Foliage* are presented in ~~Figs. 12~~Fig. 6C and ~~13~~Fig 6D, respectively. The neutron intensity ~~profiles are~~is provided for a scenario with no vegetation~~, the Gludsted Plantation reference model (model: *100 t/ha*)~~ and models with biomass equivalent to dry above-ground biomass of: 50 t/ha, 100 t/ha (Gludsted Plantation), 200 t/ha and 400 t/ha. ~~In order to calculate the relative changes listed in Table 5, the model with biomass equivalent to 100 t/ha dry above-ground biomass with the same forest canopy conceptualization is used.~~

~~***Figure 12 and Figure 13 are inserted here***~~

Forest biomass is seen to significantly alter the thermal and epithermal neutron intensity ~~profiles~~ both with regards to the differences between ground and canopy level neutron intensity, and ground level ~~thermal-to-epithermal neutron intensity~~t/e ratios (Figures ~~12~~6C and ~~13~~6D). The direction and magnitude of these changes are found to be rather different depending on the two forest canopy conceptualizations. For the Model *Tree trunk, Foliage, Air* the increase in biomass results in an increase in thermal neutron intensity ~~(Figure 12A)~~ while the epithermal neutron intensity decreases (Figure ~~12B).~~6C). The neutron intensity depends on how many neutrons are produced, down-scattered to lower energies and absorbed. Including biomass to a system increases the concentration of hydrogen and leads to reduced neutron intensity as the moderation and absorption is intensified. Despite this, increased thermal neutron intensity is provided with greater amounts of forest biomass. We hypothesize that forest biomass enhances the rate of moderation more than the rate of absorption. Thus higher thermal neutron intensity is obtained as the number of thermal neutrons generated by the moderation of epithermal neutrons exceeds the number of thermal neutrons absorbed. This behavior may be due to the large volume of air within the forest canopy. The probability of thermal neutrons to interact with elements within this space is low as the density of air is low. The effect at ground level is almost ~~constant~~the same up to an elevation of 20 m, but decreases sharply near the top of the forest canopy~~.~~ (not presented here).

Increasing the biomass in the Model *Foliage* from 0 t/ha to 50 t/ha (Figure ~~13~~6D) results in a considerable increase in ground level thermal neutron intensity (136 cts/hrs, Table ~~5~~6) while at canopy level thermal neutron intensity is almost unaltered. A further increase in biomass (>50 t/ha) decreases both ground and canopy level thermal neutron intensities. This decrease is greatest at canopy level resulting in a less steep profile slope for models with larger quantities of biomass (Figure 13A). The epithermal neutron intensity decreases at ground level and increase proportionally at canopy level with increasing amounts of biomass (Figure 13B).. The epithermal neutrons produced in the ground escape to the air and are moderated by the biomass, resulting in reduced epithermal neutron intensity with greater amounts of biomass. All models provide in accordance to theory increasing epithermal neutron intensity with height, yet, the reduced steepness of the neutron height profiles with added biomass is unexplained. Oppositely to Model *Tree trunk, Foliage, Air*, the ground level thermal neutron intensity decreases with added biomass. This may be due to the elemental concentration. Here, no space is occupied by a material of very low elemental density and may lead to an increased absorption of thermal neutrons.

As shown in Figs. 4, 123, 6C and 136D the resulting thermal and epithermal neutron intensity profiles depend highly on the chosen model-setup (forest conceptualization). At this stage, we cannot determine which conceptualization is more realistic, and we therefore choose to use both conceptualizations in the further analysis.

Figure 14 presents measured and modeled difference in ground and canopy level thermal neutron intensity (Figure 14A – 14C), and ground and canopy level epithermal neutron intensity (Figure 14D - 14F), respectively, for different amounts of forest biomass when the reference forest canopy conceptualization is used (Model *Tree trunk, Foliage, Air*). These differences are plotted against ground level thermal neutron intensity (Figures 14A and 14D), ground level epithermal neutron intensity (Figures 14B and 14E), and volumetric soil moisture estimated using the N_0-method (Desilets et al., 2010) (Figures 14C and 14F). In the modeling we have varied both the soil moisture (six values from dry to saturation) and the biomass (five different values from 0 t/ha to 400 t/ha), resulting in a total of 30 combinations. The measurements are provided as daily averages, biweekly averages and as a total average of the two-year-period.

Figure 14 is inserted here

The effect of forest biomass is apparent considering the modeled differences between ground and canopy level thermal neutron intensity against ground level epithermal neutron intensity (Figure 14B) and volumetric soil moisture (Figure 14C). Overall, the difference increases with greater amounts of biomass, with the most substantial change occurring from 0 t/ha to 50 t/ha. A similar positive correlation is observed between the difference in ground and canopy level epithermal neutron intensity and biomass. However, here the relationship exists when the differences are plotted against ground level thermal neutron intensity (Figure 14D) and volumetric soil moisture (Figure 14F).

Overall, the measured and modeled differences in ground and canopy level thermal and epithermal neutron intensities are of the same magnitude. However, the measurements do not fall onto a modeled curve representing a constant biomass value and the model underestimates the measured differences. The mean measured difference in ground and canopy level epithermal neutron intensity (two-year-period) is similar to the difference modeled for a forest of 400 t/ha dry above-ground biomass when related to ground level thermal neutron intensity (Figure 14D) and volumetric soil moisture (Figure 14F).

Considering biweekly averages the measured differences are very variable and corresponds both to models of very low (close to no vegetation) and very high amounts of biomass (> 400 t/ha dry above-ground biomass).

In Fig. 15 are the results for Model *Foliage* presented. Measured and modeled difference in ground and canopy level thermal neutron intensity (Figures 15A and 15C), and epithermal neutron intensity (Figures 15D – 15F) are shown for different amounts of forest biomass. Similar to Fig. 14, the differences are plotted against ground level thermal neutron intensity (Figures 15A and 15D), ground level epithermal neutron intensity (Figures 15B and 15E), and volumetric soil moisture estimated using the N_0-method (Desilets et al., 2010) (Figures 15C and 15F).

Figure 15 is inserted here

Again a positive correlation is found between the differences between ground and canopy level neutron intensities and the amount of biomass. The difference in neutron intensity is increased compared to Fig. 14, and all six subplots in Fig. 15 have distinct relations for each biomass value. Compared to the results of Model *Tree trunk, Foliage, Air* (Figure 14), the modeled differences in ground and canopy level neutron intensity are overestimated, however, only slightly for epithermal neutron intensity plots (Figures 15D – 15F). Here, the total average of the entire two year measurement period is found to agree reasonably with modeling and the range of measured differences (biweekly averages) is within the modeled differences provided by models of forest biomass equivalent to 0 t/ha to 100 t/ha dry above-ground biomass. The major change in differences between ground and canopy level thermal neutron intensity is seen to occur between the model with no biomass and the forest with 50 t/ha dry above-ground biomass (around 150 cts/hr). Only minor changes in the differences occur with increasing biomass above 50 t/ha, i.e. the addition of 350 t/ha dry above-ground biomass (from 50 t/ha to 400 t/ha dry above-ground biomass) only increases the difference in thermal neutron intensity with around 40 cts/hr.

One can also potentially use the thermal-to-epithermalOverall, a positive correlation is found for the differences between ground and canopy level neutron intensity (thermal and epithermal neutron energies) and the amount of biomass (Figures 6C and 6D, and Table 6). However, the Model *Tree trunk, Foliage, Air* and Model *Foliage* provides different relationships, and measurements and modeling are not fully in agreement. Alternatively, one can also potentially use the t/e ratio at the ground level to assess biomass. The advantage is that only one station is needed - and that at a convenient location. This would also allow for surveys of biomass estimations to be conducted from mobile cosmic-ray neutron intensity detector systems, e.g. installed in vehicles. As stated previously, we consider combined measurements of thermal and epithermal neutron intensities to be appropriate at Gludsted Plantation due to reasonably lateral homogeneity in soil, litter and vegetation prevails at the field site.

The measured and modeled ratios are again provided using both forest canopy conceptualization, i.e. Model *Tree trunk, Foliage, Air* (Figure 168) and Model *Foliage* (Figure 179). The ratios are plotted against A) ground level thermal neutron intensity, B) ground level epithermal neutron intensity, and C) soil moisture estimated using the N_0-method (Desilets et al., 2010). Like before, measurementsMeasurements are provided as daily averages, biweekly averages and as a total average of the whole two-year-period.

Figure ~~16~~8 and Figure ~~17~~9 are inserted here

The modeled ~~thermal-to-epithermal~~ ground level t/e ratio increases with forest biomass (Figures ~~16~~8 and ~~17). The~~9). Drying or wetting of soil change the thermal and epithermal neutron intensity proportionally and the ratios are accordingly found to be independent of changes in the ground level thermal neutron intensity, the ground level epithermal neutron intensity and volumetric soil moisture. However, this independence is not seen in the measurements, where the ground level epithermal neutron intensity and soil moisture (Figures ~~16C and 17C) in particular seem to impact the ratio. A fairly proportional increase in the ground level thermal-to-epithermal ratio with respect to greater amounts of biomass is found when using the reference conceptualization of Model *Tree trunk, Foliage, Air* (Figure 16). Contrarily, when using Model *Foliage* (Figure 17), a more uneven increase in the ratio with increasing amounts of biomass is provided. A major increase in the ground level thermal-to-epithermal neutron ratio of around 0.22 appears from no vegetation to a dry above-ground biomass of 50 t/ha. However, additional amounts of biomass only increase the ground level thermal-to-epithermal ratio slightly. With additional 350 t/ha biomass (from 50 t/ha to 400 t/ha dry above-ground biomass) the ratio increases by only 0.05 cts/hr.~~

~~A remarkably fit of measurements and modeling can be seen in Fig. 16. The two-year-average measurement is consistent with the reference model estimate of 100 t/ha dry above-ground biomass and the biweekly averages of measurements are all within the ratios modeled for biomass of 50 t/ha - 200 t/ha.~~ 8C and 9C) in particular seem to impact the ratio.~~For the Model *Foliage* in Fig. 17, the two-year-average of the measured ratios corresponds to approximately the modeled value of 50 t/ha dry above-ground biomass. Moreover, the biweekly averages of the measurements exceed the lower and upper boundary of ratios provided by the models of 50 t/ha and 400 t/ha dry above-ground biomass.~~

~~Contrary to the modeling results, our measurements suggest a dependence of ground level thermal-to-epithermal neutron ratio to soil moisture changes.~~ The discrepancy of measurements and modeling could be related to: 1) shortcomings in the model setup, i.e. a need for an even more realistic forest conceptualization, and more detailed and up-to-date forest information. A model including a sufficient representation of the field site will provide neutron height profiles and t/e ratios more representative of the real conditions, 2) discrepancy of measured and modeled energy ranges as discussed in Andreasen et al. (2016), and 3) unrepresentative biomass estimate. The 100 t/ha dry above-ground biomass was estimated using LiDAR images from 2006 and 2007 and therefore not completely representative of the 2013-2015 conditions (because of tree growth). Furthermore, the biomass estimate varied considerably within the image (standard deviation = 46 t/ha), and the image coverage did not fully match the footprint of the cosmic-ray neutron intensity detector.

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Overall, for the Model *Tree trunk, Foliage, Air* in Fig. 8, a remarkable agreement is seen when comparing the two-year-average of the measured ratio with the modeled value of Gludsted Plantation (100 t/ha dry above-ground biomass, Figure 8). The biweekly averages of measurements are all within the ratios modeled for biomass of 50 t/ha - 200 t/ha. For the Model *Foliage* in Fig. ~~The ground level thermal-to-epithermal neutron intensity~~9 the measured ratio is in better agreement with a lower biomass (50 t/ha dry above-ground biomass) and the biweekly averages of the measurements are much wider exceeding both the lower and upper boundary of ratios provided by the models of 50 t/ha and 400 t/ha dry above-ground biomass.

A fairly proportional increase in the ground level t/e ratio with respect to greater amounts of biomass is found when using Model *Tree trunk, Foliage, Air* (Figure 10). Contrarily, when using Model *Foliage*, a more uneven increase in the ratio with increasing amounts of biomass is provided. A major increase in the ground level t/e ratio of around 0.22 appears from no vegetation to a dry above-ground biomass of 50 t/ha. However, additional amounts of biomass only increase the ground level t/e ratio slightly. With additional 350 t/ha biomass (from 50 t/ha to 400 t/ha dry above-ground biomass) the t/e ratio increases by only 0.05 cts/hr.

Figure 10 is inserted here

The modeled ground level t/e ratio is compared with two additional field sites close to Gludsted Plantation. The three field sites have similar environmental settings (e.g. neutron intensity, soil chemistry), though different land covers with different amounts of biomass (stubble pasture and heathland).

At Voulund Farmland the ground level ~~thermal-to-epithermal~~t/e ratio was measured to be 0.53 and 0.58 on September 22nd and September 23rd 2015, respectively. Only minor amounts of organic matter were present in the stubble and residual of spring barley harvested in August 2015. Additionally, the ground level ~~thermal-to-epithermal~~t/e ratio was determined based on modeling of bare ground and site specific soil chemistry measured at Voulund Farmland (Andreasen et al., 2016). The modeled ratio was found to be 0.56 in agreement with the measured ratios. The ratio modeled based on the non-vegetated conceptualization of Gludsted Plantation was slightly higher (0.60, see Figures 16 and 17). Here, a 10 cm thick litter layer was included in the model. The sensitivity analysis on the effect of litter layer on neutron intensity (Figure 8 and Table ~~5~~6) implies that lower ~~thermal-to-epithermal neutron intensities~~ground level t/e ratios are found at locations with a thin or no litter layer.

The ground level ~~thermal-to-epithermal neutron~~t/e ratio at the Harrild Heathland was measured to 0.66 during the period October 27 to November 16 2015. The ratio is slightly higher than the non-vegetated model for Gludsted Plantation~~, yet, both~~. Both field sites have a considerable layer of litter, and ~~some amount of~~ the slightly higher t/e ratio relative to the non-vegetated Gludsted Plantation may be due to biomass in the form of grasses, heather plants and bushes ~~are~~ present at ~~the~~ Harrild Heathland.~~ The slightly higher ratio at Harrild Heathland relative to the non-vegetated Gludsted Plantation may be due to this smaller amount of biomass.~~ At Gludsted Plantation, the ratio is 0.73 for dry above-ground biomass equivalent of 50 t/ha. Accordingly, the ratio measured at Harrild Heathland is somewhere in between the ratio modeled for a non-vegetated field site and a field site with biomass equivalent to 50 t/ha dry above-ground biomass.

The modeled decrease in ground level ~~thermal-to-epithermal~~t/e ratios with smaller amounts of biomass are in line with the measurements conducted at the three field sites of similar soil chemistry and dissimilar land covers in terms of litter and vegetation.

Detecting the ground level ~~thermal-to-epithermal neutron~~t/e ratio at locations of known biomass should be accomplished to test the suggested relationship obtained using the forest canopy conceptualization of Model *Tree trunk, Foliage, Air*. We recommend a detection system with higher sensitivity to be used when a location of low neutron intensity rates (like Gludsted Plantation) is surveyed, unless long periods of measurements can be conducted at each measurement location. This can be accomplished by using larger sensors, an array of several sensors and/or sensors that are more efficient, as is done in roving surveys (Chrisman and Zreda, 2013; Franz et al., 2015).

~~5~~.4. Conclusion

The potential of applying the cosmic-ray neutron intensity method for other purposes than soil moisture detection was explored using profile and time-series measurements of neutron intensities combined with neutron transport modeling. The vegetation and subsurface layers of the forest model-setup were described by average measurements and estimates~~ and a remarkable agreement was found for measured and modeled thermal and epithermal neutron intensity profiles without adjusting parameters and variables. Following, a~~. Four forest canopy conceptualizations of increasing complexity were used. Without adjusting parameters and variables, modeled thermal and epithermal neutron intensity profiles compared fairly well with measurements, yet, some deviations from measurements were observed for each of the four forest canopy conceptualization models. The more appropriate forest canopy conceptualization was not obvious from the results as the best fit to thermal neutron measurements was found using complex forest canopy conceptualization, including a tree trunk and multiple materials, while the better fit to epithermal neutron measurements was found using the most simple forest canopy conceptualization, including a homogenous layer of foliage material. A sensitivity analysis was performed to quantify the effect of the forests governing parameters/variables on the neutron transport profiles.

~~The ground level thermal-to-epithermal~~The sensitivity of canopy interception, dry bulk density of litter and mineral soil, and soil chemistry on neutron intensity was found to be small. The ground level t/e neutron ratio was found to increase with increasing amounts of canopy interception and to be independent of ground level thermal neutron intensity, ground level epithermal neutron intensity and soil moisture. However, the increase was minor and the measurement uncertainty exceeds the signal of canopy interception at a timescale appropriate to detect canopy interception at Gludsted Plantation (half-hour to hourly). However, the signal of canopy interception can potentially be isolated in measurements from locations of higher neutron intensities (lower latitudes and/or higher altitudes) with canopy interception of longer residence time and larger storage capacity (e.g. snow). ~~After soil moisture, the next most important variables affecting neutron~~Neutron intensity ~~profiles were the thicknesses of the~~was found to be more sensitivity to litter layer, soil moisture and ~~the amount of above-ground~~ biomass at the forest field site. An increased litter layer at the forest floor resulted in reduced neutron intensities, particularly for epithermal neutrons. ~~Increased amounts of forest biomass altered the thermal and epithermal neutron intensity profiles significantly. Both~~Forest biomass was found to alter the thermal and epithermal neutron transport significantly, both in terms of the shape of the neutron profiles and the t/e neutron ratios. The response to altered amounts of biomass on thermal and epithermal neutron intensity is non-unique for the simple and complex forest conceptualization and further advancement of the forest representation is therefore necessary. Still, both the difference between ground and canopy level thermal and epithermal neutron intensity, respectively, and the ground level ~~thermal-to-epithermal neutron~~t/e ratios were changed with additional amounts of biomass~~.~~ using the simple and complex forest canopy conceptualization.

The best agreement between measurements and modeling was obtained for the ground level ~~thermal-to epithermal~~t/e neutron ratio using a model with a complex forest canopy conceptualization. Furthermore, the modeled ratios were found to agree well with two nearby field sites with different ~~land-covers~~amounts of biomass (a bare ground agricultural field and a heathland field site).

~~6.~~5. Acknowledgements

We acknowledge The Villum Foundation (www.villumfonden.dk) for funding the HOBE project (www.hobe.dk). Lars M. Rasmussen and Anton G. Thomsen (Aarhus University) are greatly thanked for the extensive help in the field. We would like to extend our gratitude to Vivian Kvist Johannsen and Johannes Schumacher from the Section for Forest, Nature and Biomass, University of Copenhagen. Finally, we also acknowledge the NMDB database (www.nmdb.eu), founded under the European Union's FP7 programme (contract no. 213007) for providing data. Jungfraujoch neutron monitor data were kindly provided by the Cosmic Ray Group, Physikalisches Institut, University of Bern, Switzerland.

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Tables

Table 1 – Dynamics of different hydrogen pools.

	Static	Quasi-static	~~Transient~~ Dynamic
Soil moisture			x
Tree roots		x	
Soil organic matter		x	
Water in soil minerals	x		
Vegetation (cellulose, water)		x	x
Snow		x	x
Puddles			x
Open water (river, sea, lake)		x	
Canopy intercepted water			x
Buildings/roads	x		
Atmospheric water vapor			x

Table 2 – Average tree height, tree diameter and dry bulk density (bd_{dry}) of the litter layer and the mineral soil at Gludsted Plantation field site. Tree height and diameter are representative of conditions for year 2012.

	Average	Standard deviation	Max.	Min.
Tree height* [m]	11	6	25	3
Tree diameter* [m]	0.14	0.08	0.34	0.03
Dry bulk density litter layer, [g cm^{-3}]	0.34	0.29	1.09	0.09
Dry bulk density mineral soil, [g cm^{-3}]	1.09	0.28	1.53	0.22

* Data obtained from the Danish Nature Agency

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Table 3 – Chemical composition of major elements at Gludsted Plantation determined using X-ray fluorescence analysis on soil samples collected in 0.20-0.25 m depth.

	Gludsted Plantation [%]
O	52.78
Si	44.86
Al	1.54
K	0.53
Ti	0.29

Table 4 – Forest properties used in modeling.

*Specific for model with forest conceptualization of Model *Tree trunk, Foliage, Air*. **Reference model.

	Models				
	No vegetation	50 t ha^{-1}	100 t ha^{-1}**	200 t ha^{-1}	400 t ha^{-1}
Dry above-ground biomass [t ha^{-1}]	0	50	100	200	400
Wet above-ground biomass [t ha^{-1}]	0	91	182	364	727
Dry below-ground biomass [t ha^{-1}]	0	12.5	25	50	100
Wet below-ground biomass [t ha^{-1}]	0	23	45	91	182
Tree trunk density [g cm^{-3}] *	-	0.83	0.83	0.83	0.83
Tree trunk radius [m] *	-	0.07	0.07	0.07	0.07
Tree height [m] *	-	25	25	25	25
Foliage density [g cm^{-3}] *	-	0.00134	0.00151	0.00185	0.00255
Foliage band [m] *	-	2.44	1.70	1.18	0.82
Sub-cell size [m x m] *	-	6.67 x 6.67	4.72 x 4.72	3.34 x 3.34	2.36 x 2.36

Table 5Table 5 – Modeled ground level (1.5 m) and canopy level (27.5 m) thermal neutron intensity and epithermal neutron intensity for the Gludsted Plantation models including four different forest canopy conceptualizations (see Fig. 3).

		Thermal 1.5 m	Thermal 27.5 m	Epithermal 1.5 m	Epithermal 27.5 m
Gludsted Plantation models (Fig. 3)	Foliage	573	207	681	813
-	Tree trunk, Air	484	272	610	695
-	Tree trunk, Foliage	536	261	619	716
	Tree trunk, Air, Foliage	504	257	623	717

Table 6 – Sensitivity in modeled ground level (1.5 m) and canopy level (27.5 m) thermal neutron intensity and epithermal neutron intensity due to (1) forest conceptualization, (2) soil moisture, (32) soil chemistry, (43) litter layer thickness, (54) mineral soil and litter dry bulk density, (6 (bd_{dry}), (5) canopy interception and (76) biomass. The sensitivity is provided in absolute values and are relative to the simulations based on the *reference model* given in Fig. 3 and Model *Tree trunk, Air, Foliage* given in Fig. 4,* and Model *Foliage***, respectively. (see Fig. 3 and Table 5). Values provided in parentheses specifies the direct effect of one-by-one excluding soil organic matter, (*third order complexity*), Gd, (*second order complexity*), below ground biomass (*first order complexity*) and site specific major elements soil chemistry.* Reference, in absolute values. (SiO_2).

		Thermal 1.5 m	Thermal 27.5 m	Epithermal 1.5 m	Epithermal 27.5 m
Conceptualization models (Fig. 4)	Tree trunk, Air, Foliage	504*	257*	623*	717*
	Foliage	70	-50	58	113
-	Tree trunk, Air	-20	15	-13	-22
-	Tree trunk, Foliage	32	4	-4	-1
Soil moisture models (Fig. 54)	0.18	504*	257*	623*	717*
Model *Tree trunk, Air, Foliage*	0.05	100	47	131	109
	0.10	45	20	58	50
	0.25	-25	-12	-27	-23
	0.35	-47	-22	-53	-45
	0.45	-59	-28	-69	-59
Soil moisture models (Fig. 65)	0.18	573***	207***	681***	813***
Model *Foliage*	0.05	119	40	142	115
	0.10	56	18	68	53

	0.25	-27	-9	-30	-23
	0.35	-50	-16	-55	-48
	0.45	-64	-21	-74	-61
Soil chemistry models (Fig. ~~7~~6)	4th order complexity	504*	257*	623*	717*
~~Model *Tree trunk, Air, Foliage*~~	3rd order complexity	19 (+19)	8 (+8)	25 (+25)	14 (+14)
	2nd order complexity	18 (-1)	9 (+1)	27 (-2)	17 (+3)
	1st order complexity	22 (+4)	10 (+1)	26 (-1)	18 (+1)
	SiO_2	27 (+5)	11 (+1)	23 (-3)	19 (+1)
Litter layer models (Fig. ~~8~~6A)	10.0 cm	504*	257*	623*	717*
~~Model *Tree trunk, Air, Foliage*~~	7.5 cm	11	4	26	22
	5.0 cm	18	9	53	41
	2.5 cm	24	12	85	71
	No litter layer	22	17	131	113
Density models ~~(Fig. 9)~~	Gludsted Plantation*	504*	257*	623*	717*
~~Model *Tree trunk, Air, Foliage*~~	Higher ~~bd_{litter}~~ litter layer bd_{dry}	-7	-5	-10	-6
	Higher ~~$bd_{mineral}$~~ mineral soil bd_{dry}	15	5	17	10
	Lower ~~bd_{litter}~~ litter layer bd_{dry}	7	2	14	10
	Lower ~~$bd_{mineral}$~~ mineral soil bd_{dry}	-26	-13	-22	-18
Canopy interception models (Fig. ~~10~~6B)	Dry canopy	504*	257*	623*	717*
~~Model *Tree trunk, Air, Foliage*~~	1 mm	4	-2	-3	0
	2 mm	7	-3	-5	5
	4 mm	15	-7	-5	2
Biomass models (Fig. ~~11~~6C)	100 t ha^{-1}	504*	257*	623*	717*
~~Model *Tree trunk, Air, Foliage*~~	No vegetation	-67	-21	99	85
	50 t ha^{-1}	-16	-8	45	33
	200 t ha^{-1}	14	2	-70	-47
	400 t ha^{-1}	21	2	-172	-116
Biomass models (Fig. ~~12~~6D)	100 t ha^{-1}	573~~*~~**	207~~*~~**	681~~*~~**	813~~*~~**
~~Model *Foliage*~~	No vegetation	-136	29	41	-28
	50 t ha^{-1}	0	24	13	-23
	200 t ha^{-1}	-9	-32	-26	22
	400 t ha^{-1}	-48	-59	-82	73

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Figures

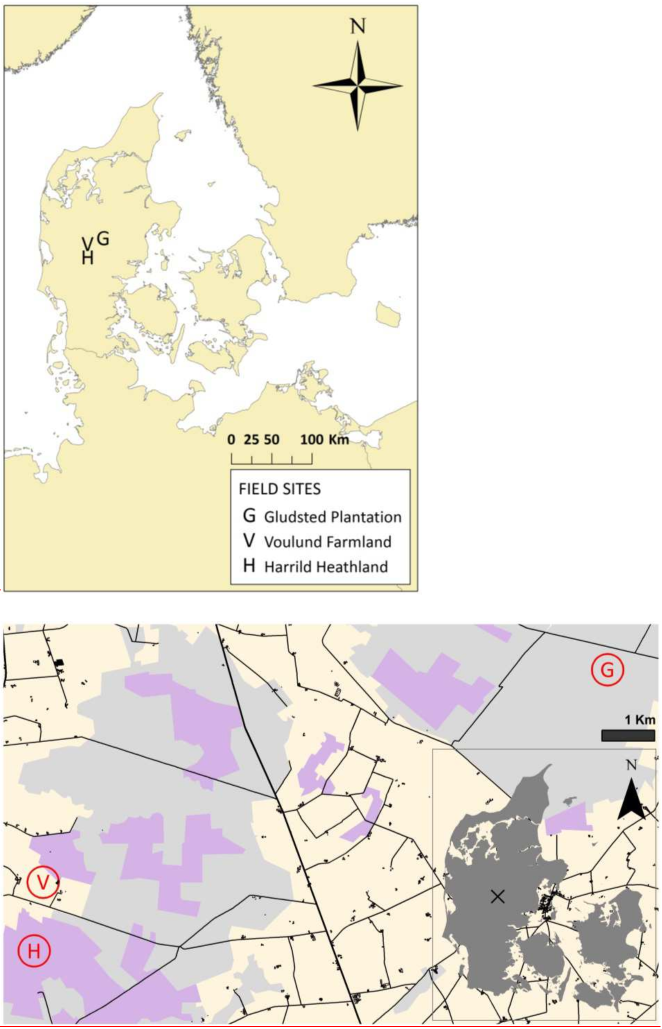


Figure 1 – Map showing the location of the three field sites; G: Gludsted Plantation, (light gray), V: Voulund Farmland (beige) and H: Harrild Heathland. (purple). The circles represent the footprint of the neutron detector (radius = 300 m).

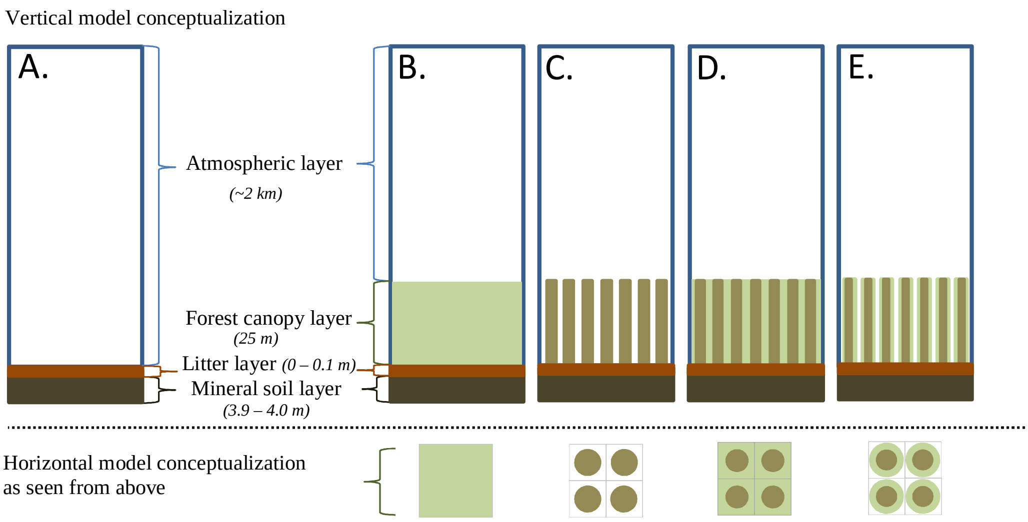
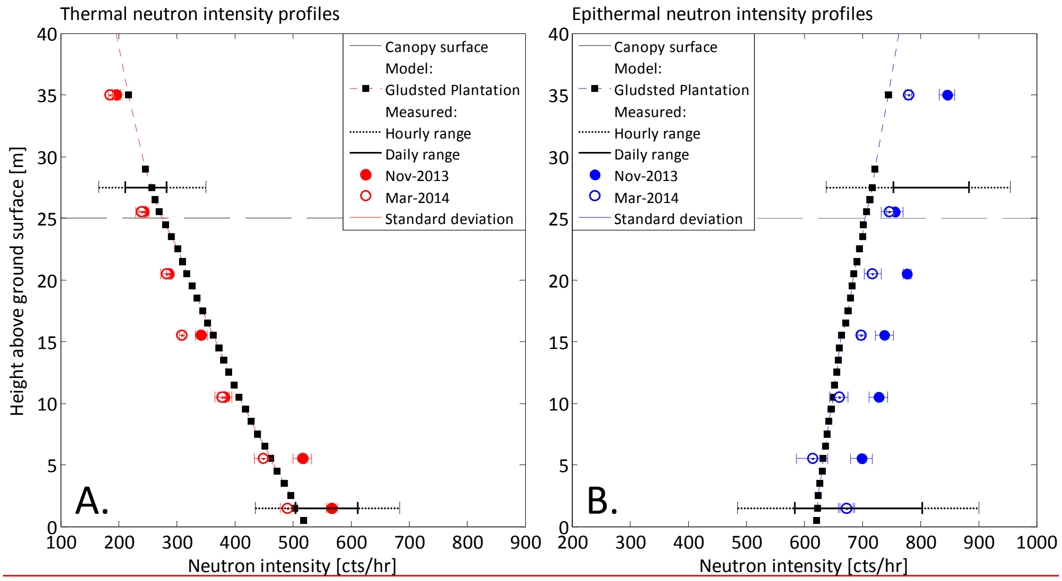


Figure 2 – Model conceptualizations of forest. A: no forest canopy layer (model name: *0 t ha*$^{-1}$); B: homogeneous foliage layer with a uniformly distributed biomass (model name: *Foliage*); C: cylindrical tree trunks with air in between (model name: *Tree trunks, Air*); D: cylindrical tree trunks with foliage in between (model name: *Tree Trunks, Foliage*); E: cylindrical tree trunks enveloped in a foliage-cover with air in between (model name: *Tree trunks, Foliage, Air*). The bottom four figures illustrate the forest conceptualization seen from above.


Thermal neutron intensity profiles
Epithermal neutron intensity profiles
Canopy surface
Model:
Gludsted Plantation
Measured:
Hourly range
Daily range
Nov-2013
Mar-2014
Standard deviation
Height above ground surface [m]
Neutron intensity [cts/hr]
A.
B.

~~Figure 3~~

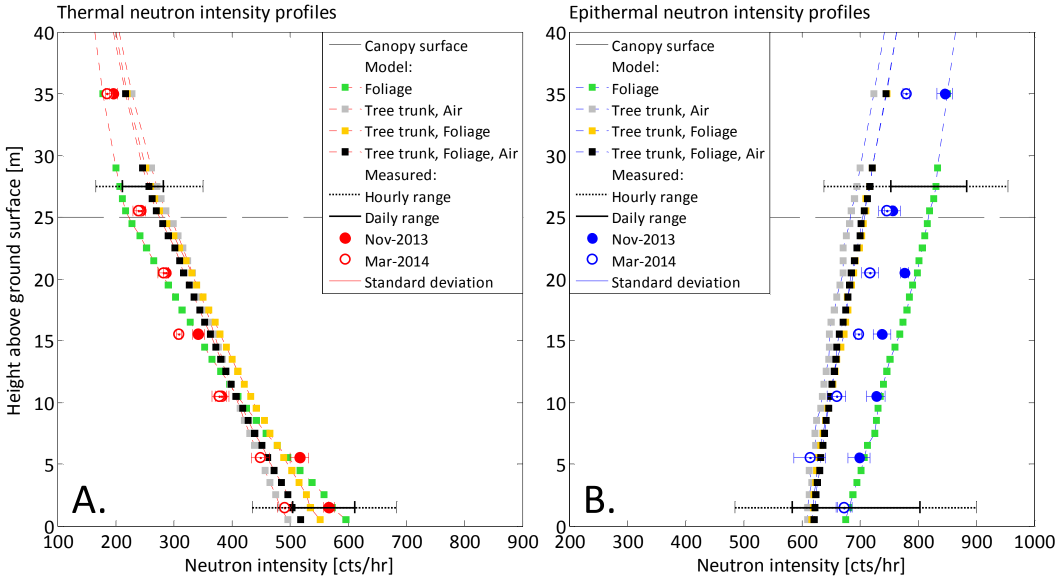

Thermal neutron intensity profiles
Epithermal neutron intensity profiles
Canopy surface
Model:
Foliage
Tree trunk, Air
Tree trunk, Foliage
Tree trunk, Foliage, Air
Measured:
Hourly range
Daily range
Nov-2013
Mar-2014
Standard deviation
Height above ground surface [m]
Neutron intensity [cts/hr]
A.
B.

Figure 3 – Gludsted Plantation reference model. Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.

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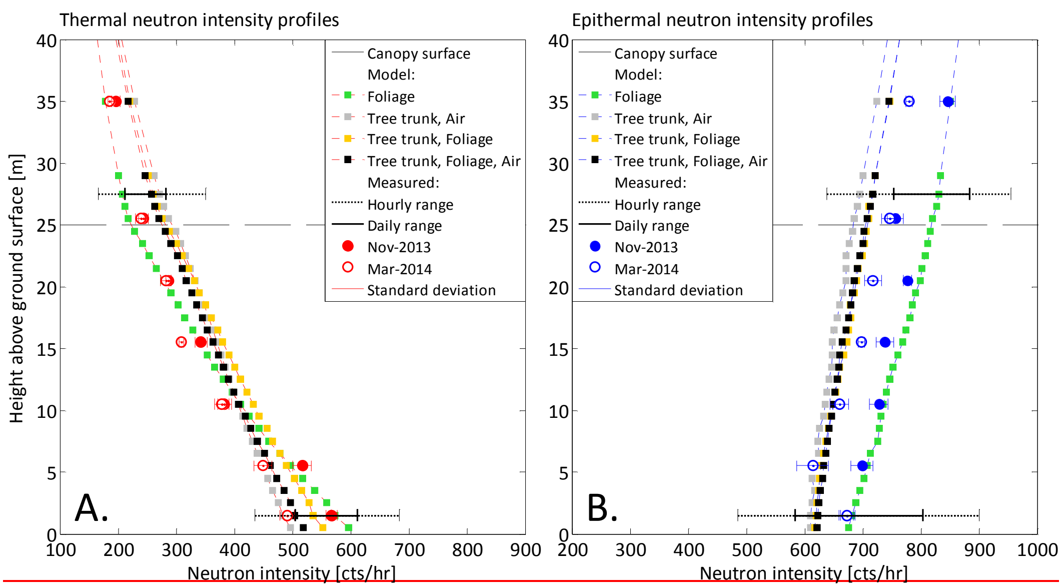


Figure 4 – Sensitivity to forest canopy conceptualization. Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015. Gludsted Plantation is modeled using four different forest canopy conceptualizations (see Figure 2).

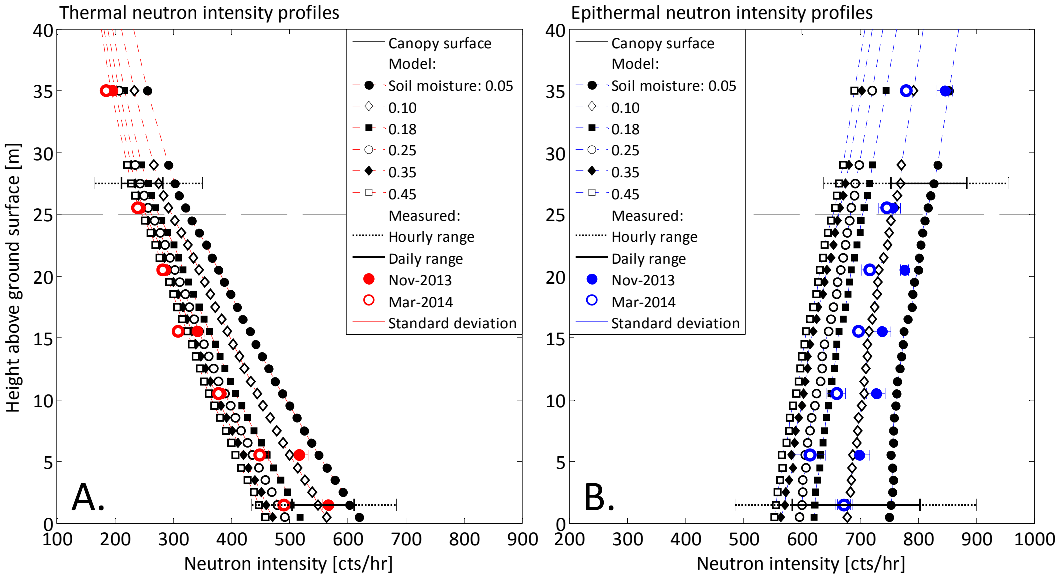


Figure 4 – Sensitivity to soil moisture (Model *Tree trunk, Foliage, Air*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.

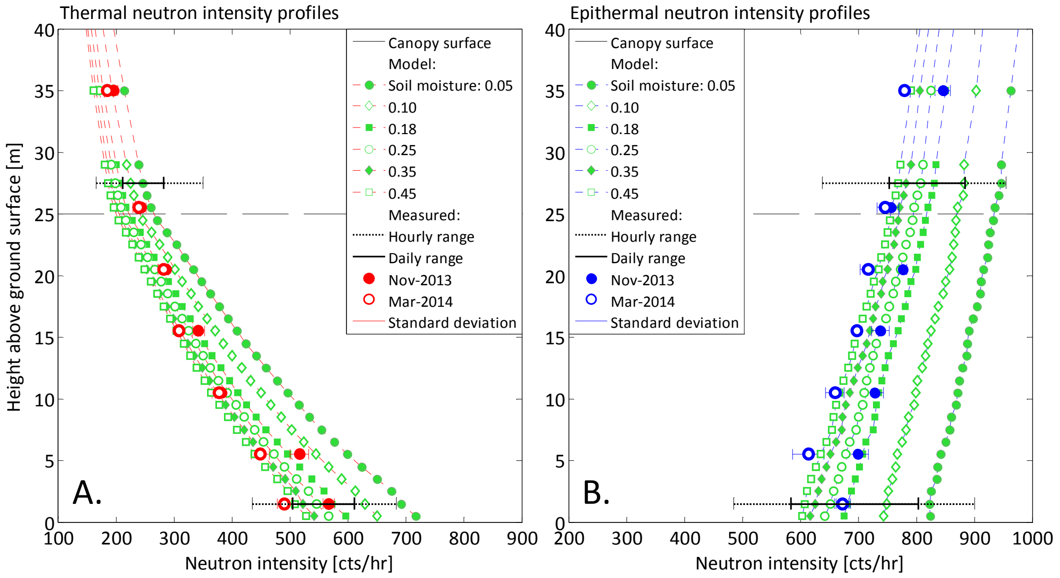
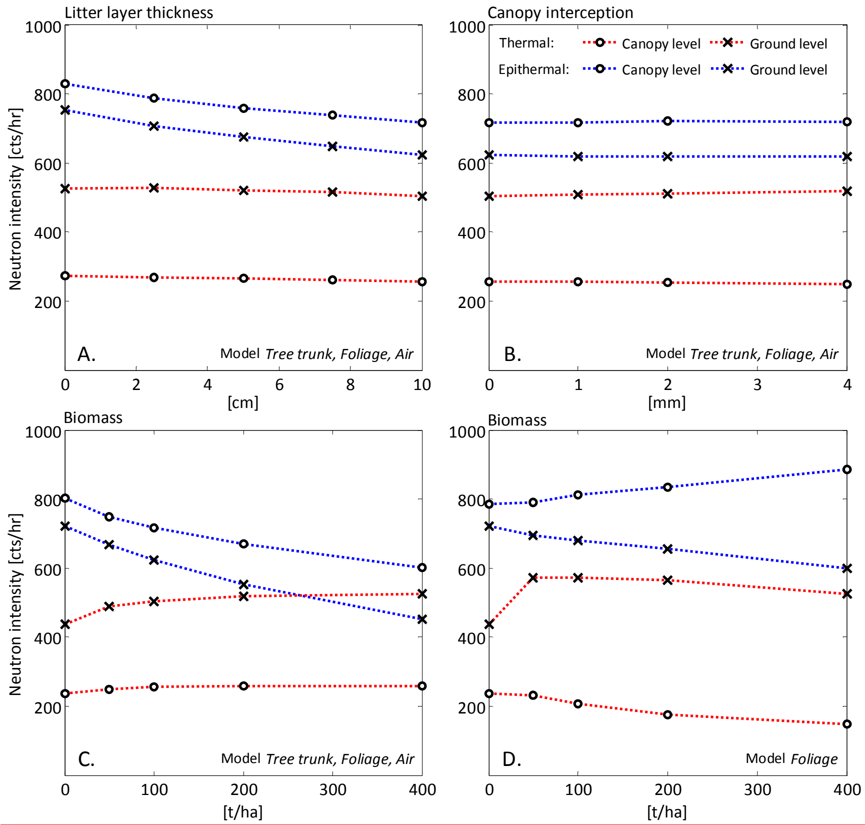


Figure 5 - Sensitivity to soil moisture (Model *Foliage*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.


Litter layer thickness
Canopy interception
Biomass
Biomass
Neutron intensity [cts/hr]
Neutron intensity [cts/hr]
Thermal:
Canopy level
Ground level
Epithermal:
Canopy level
Ground level
A.
Model *Tree trunk, Foliage, Air*
B.
Model *Tree trunk, Foliage, Air*
C.
Model *Tree trunk, Foliage, Air*
D.
Model *Foliage*
[cm]
[mm]
[t/ha]
[t/ha]
1000
800
600
400
200
0
2
4
6
8
10
1
3
100
300

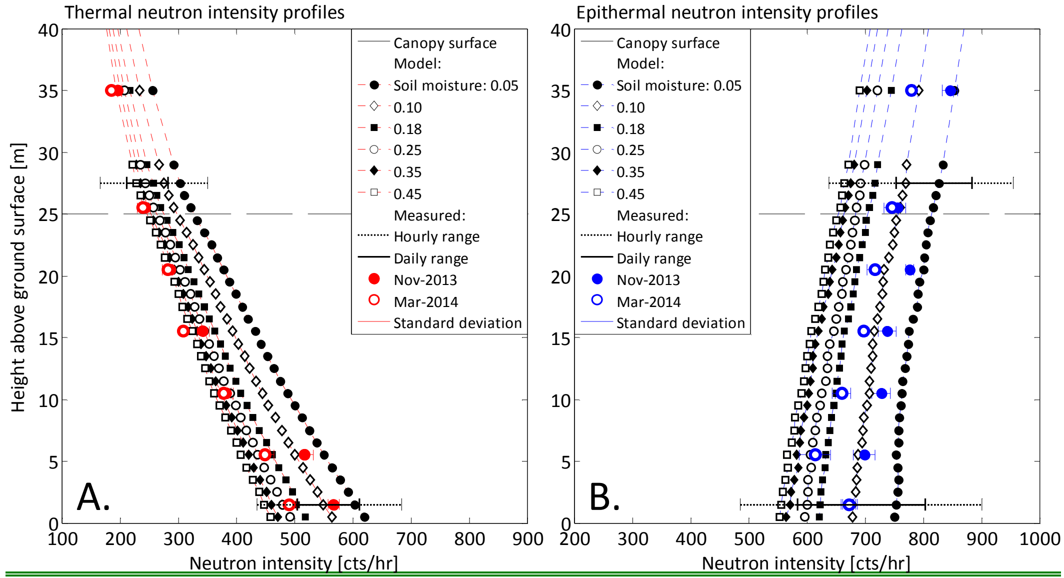


Figure 5 6 - Sensitivity to soil moisture ((A.) litter layer thickness using Model *Tree trunk, Foliage, Air*). Measured , (B.) canopy interception using Model *Tree trunk, Foliage, Air*, (C.) and modeled (A.) thermalD) biomass using Model *Tree trunk, Foliage, Air*, and (B.) Model *Foliage*, respectively. Thermal and epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.

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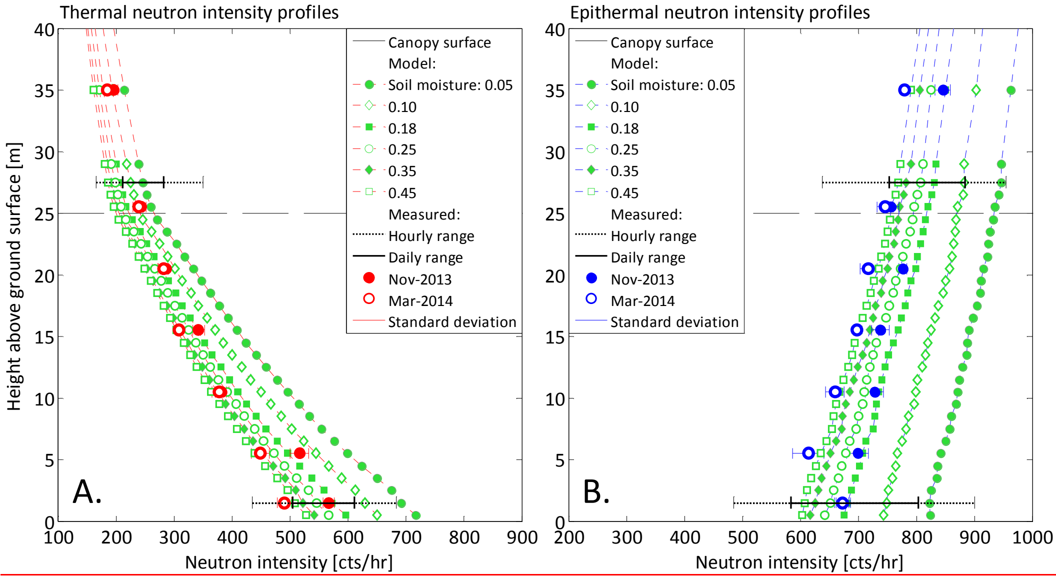
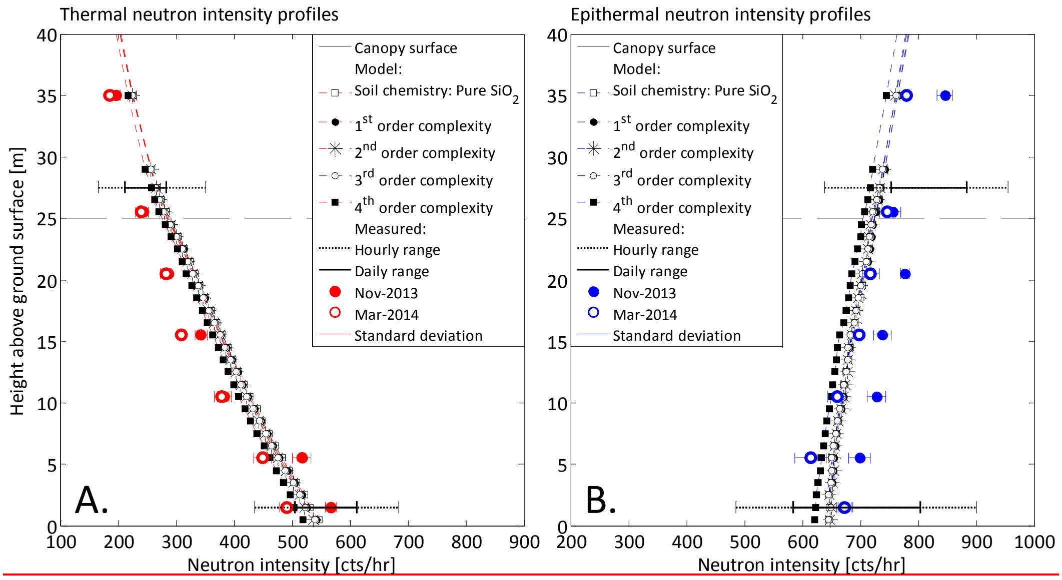


Figure 6 - Sensitivity to soil moisture (Model *Foliage*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.



~~Figure 7 - Sensitivity to soil chemistry complexity (Model *Tree trunk, Foliage, Air*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Five models of increasing complexity in soil chemistry are shown: 1) Pure SiO_2, 2) First order complexity; site specific soil chemistry of the major elements (XRF), 3) Second order complexity; XRF and a Gadolinium (Gd) concentration of 0.51 ppm, 4) Third order complexity; XRF, Gd and an assumed below ground dry biomass of 25 t ha^{-1} (roots), and 5) Fourth order complexity is the *reference model* shown in Fig. 3 and includes XRF, Gd, roots and measured soil organic matter. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.~~

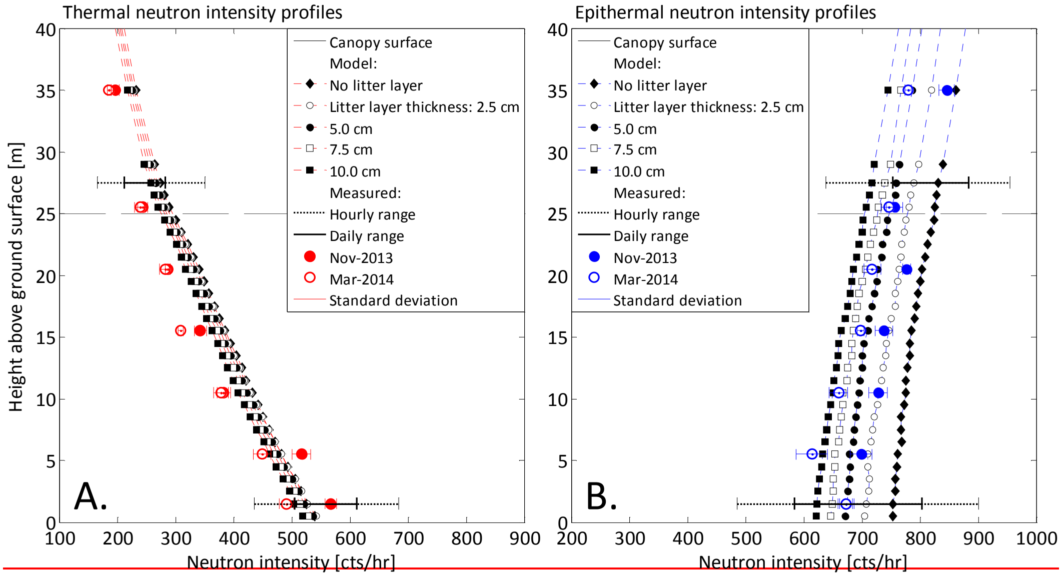


Figure 8 – Sensitivity to litter layer thickness (Model *Tree trunk, Foliage, Air*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.

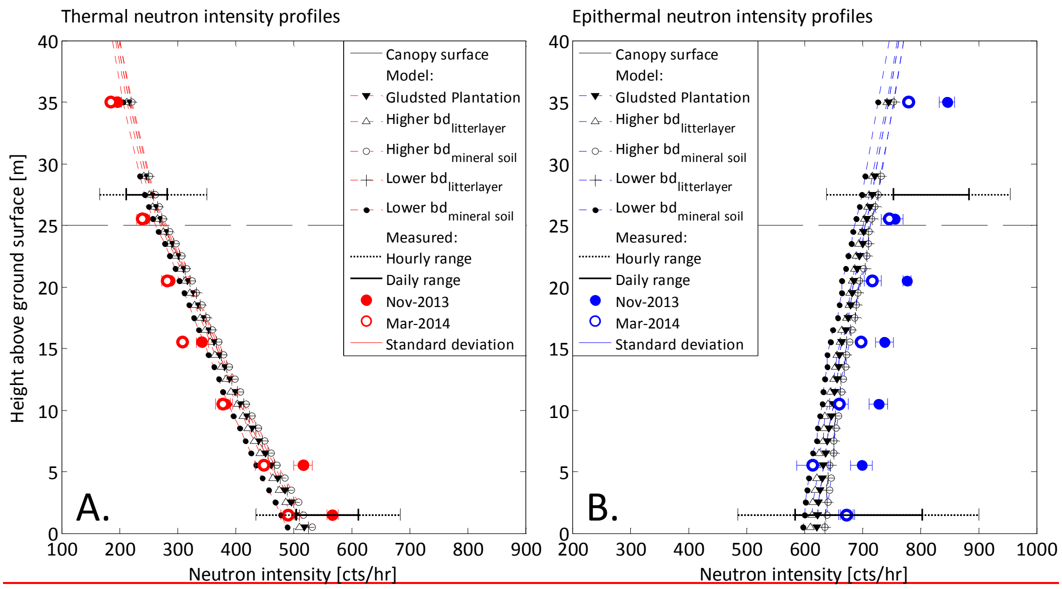
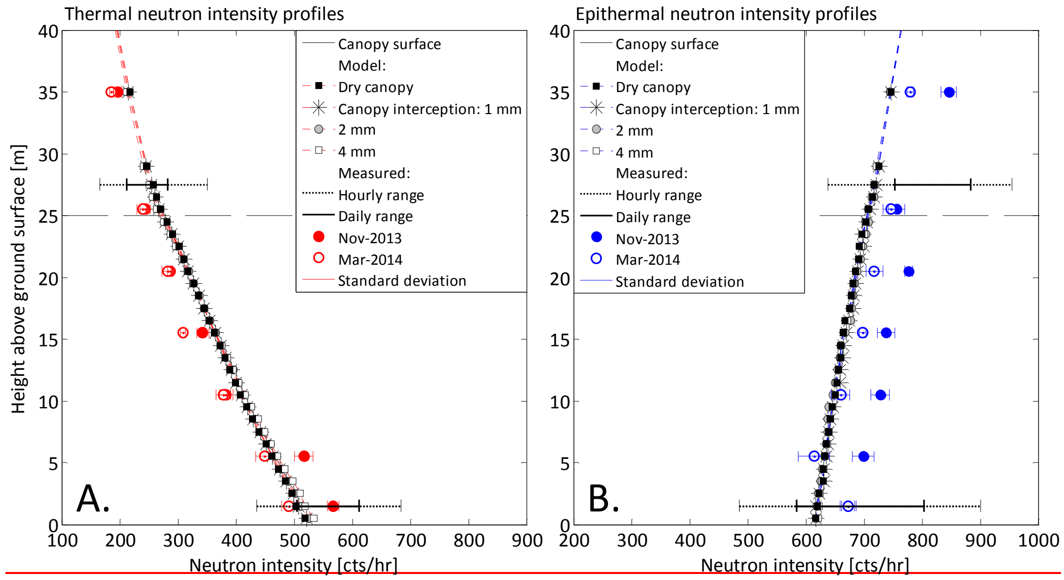
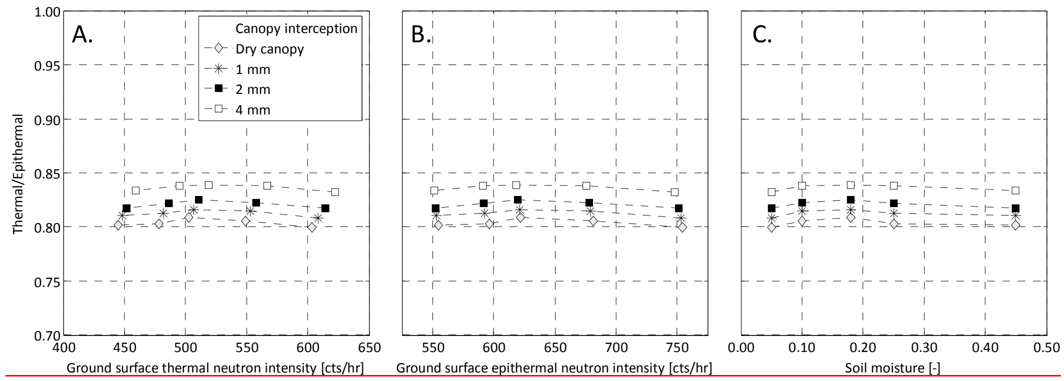


Figure 9 - Sensitivity to litter and mineral soil bulk density (bd) (Model *Tree trunk, Foliage, Air*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Gludsted Plantation model is the *reference model* with bd_{dry} = 0.34 g cm^{-3} for the litter layer and bd_{dry} = 1.09 g cm^{-3} for the mineral soil (Table 2). Relative to the *reference model* models of higher and lower litter and mineral soil bulk densities are shown: 1) Higher $bd_{litterlayer}$ (litter layer bd_{dry} = 0.50 g cm^{-3}), 2) Higher $bd_{mineral\ soil}$ (mineral soil bd_{dry} = 1.60 g cm^{-3}), 3) Lower $bd_{litterlayer}$ (litter layer bd_{dry} = 0.20 g cm^{-3}), and 4) Lower $bd_{mineral\ soil}$ (mineral soil bd_{dry} = 0.60 g cm^{-3}). Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.



~~Figure 10 – Sensitivity to canopy interception (Model *Tree trunk, Foliage, Air*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.~~



~~Figure 11~~

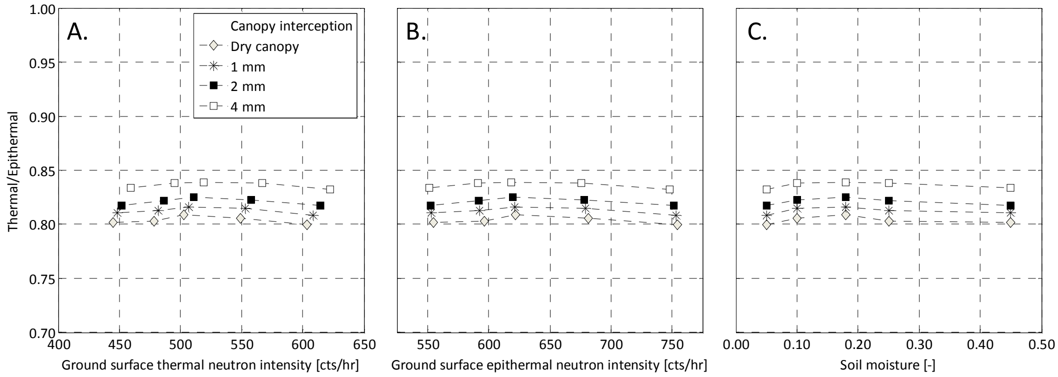
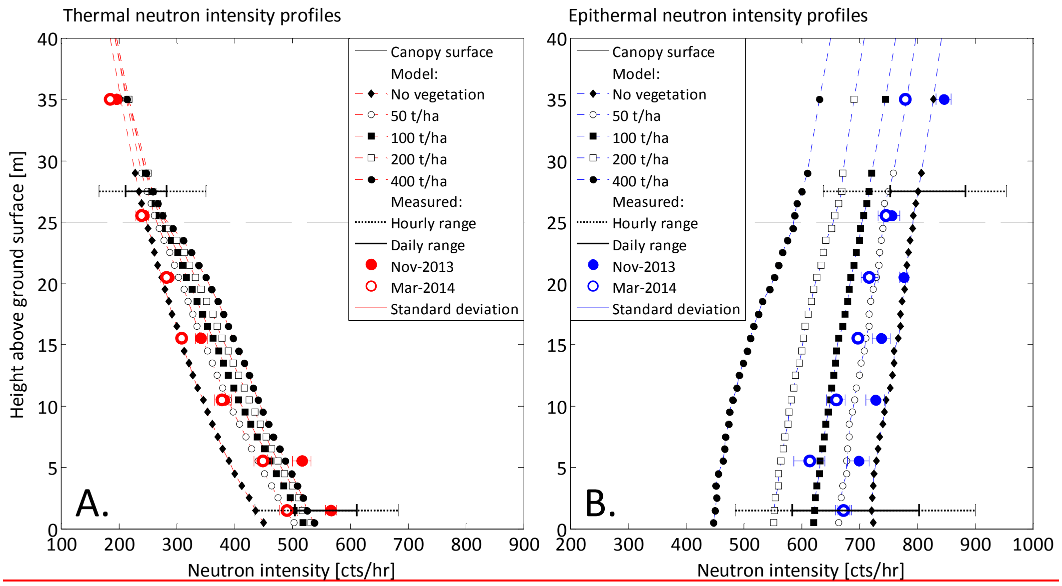
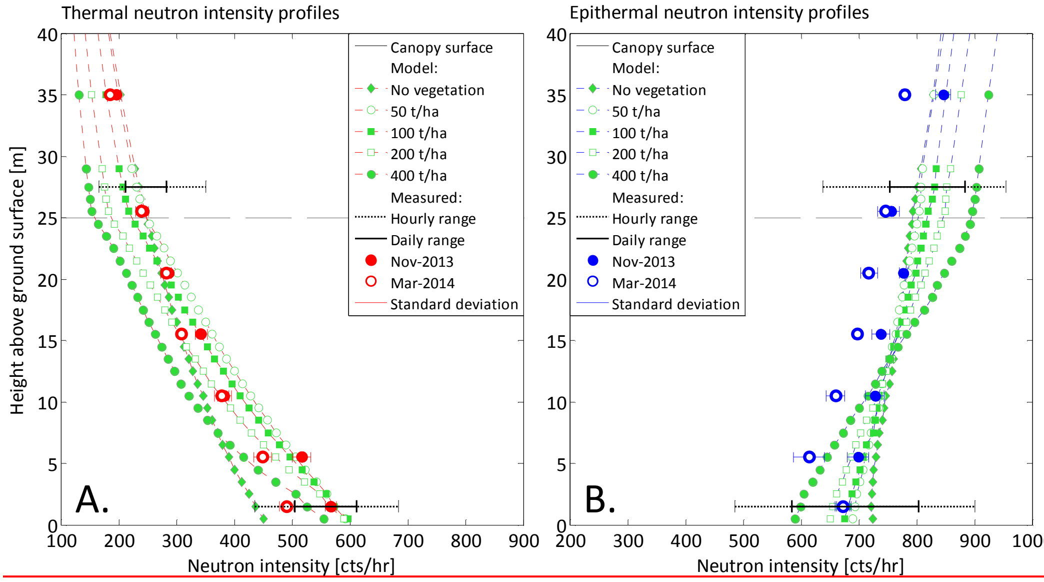


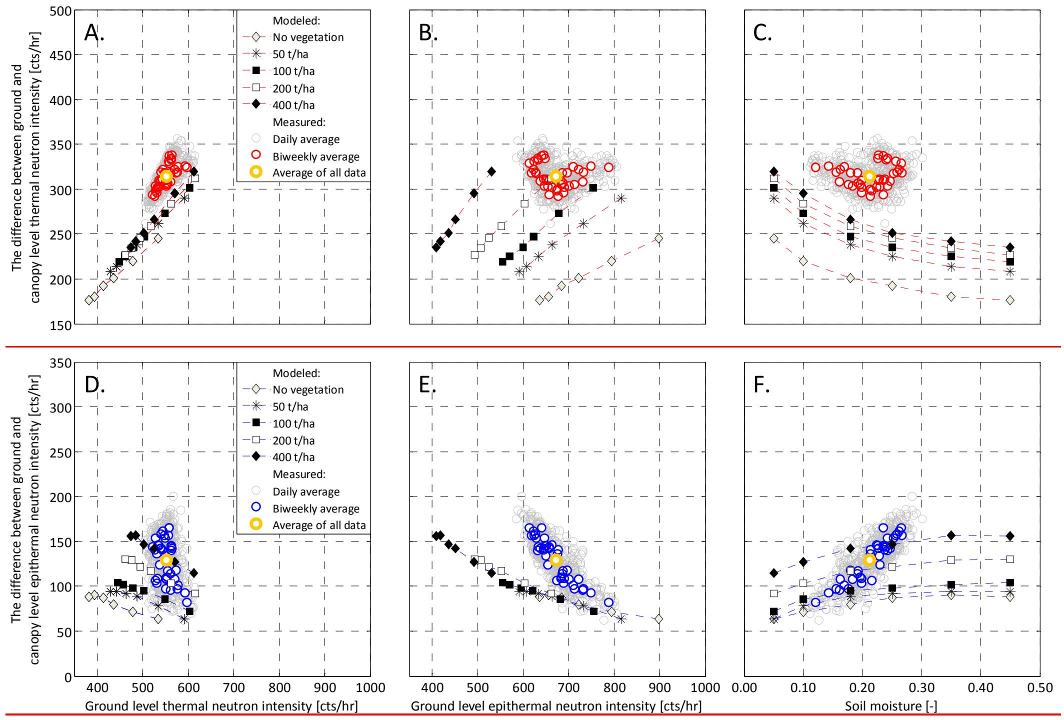
Figure 7 – Modeled ground level thermal-to-epithermal neutron intensity ratios using the Model *Tree trunk, Foliage, Air* for a dry forest canopy and canopy interception of 1 mm, 2 mm and 4 mm. plotted against modeled: A.) ground level thermal neutron intensity, B.) ground level epithermal neutron intensity, and C.) volumetric soil moisture.



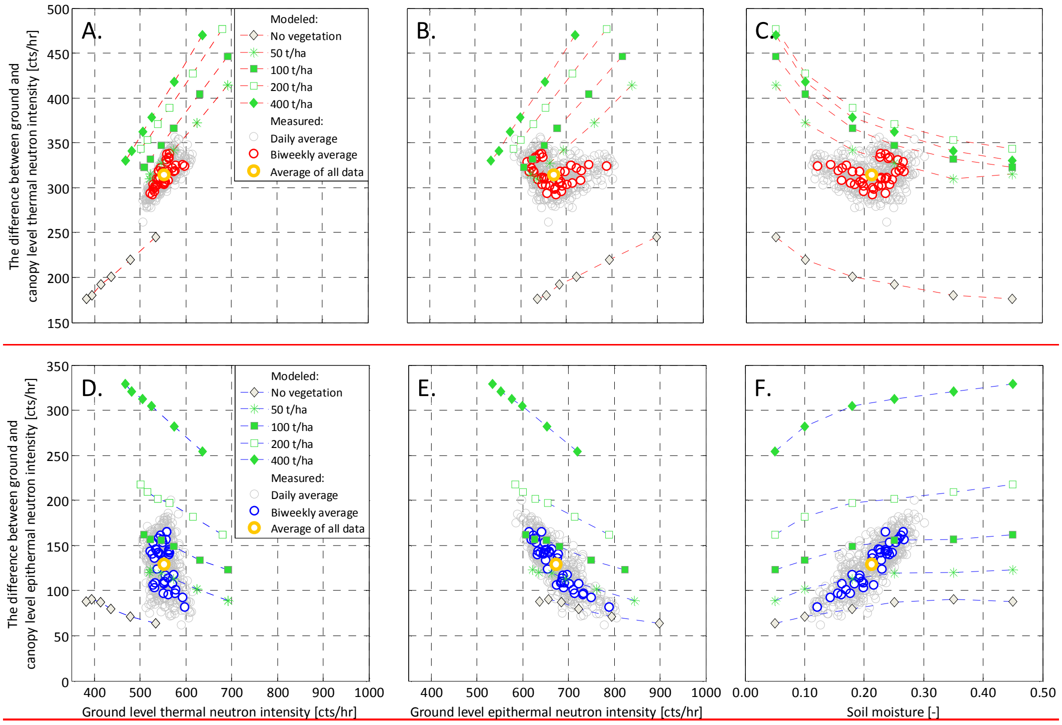
~~Figure 12 – Sensitivity analysis to forest biomass (Model *Tree trunk, Foliage, Air*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.~~



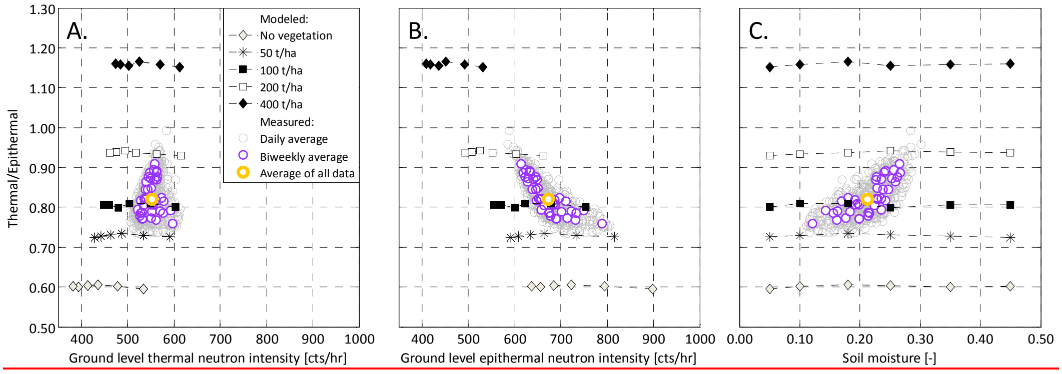
~~Figure 13 – Sensitivity analysis to forest biomass (Model *Foliage*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Here, the forest conceptualization of model Foliage is used (see Figure 2B and Figure 7). Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.~~



~~Figure 14 – Neutron intensities measured at Gludsted Plantation in the time period 2013-2015 and modeled using the Model *Tree trunk, Foliage, Air*. Difference in ground and canopy level thermal (A. – C.) and epithermal neutron intensity (D. – F.) plotted against measured and modeled: A. and D.) ground level thermal neutron intensity, B. and E.) ground level epithermal neutron intensity, and C. and F.) volumetric soil moisture.~~



~~Figure 15 - Neutron intensities measured at the Gludsted Plantation in the time period 2013-2015 and modeled using the Model *Foliage*. Difference in ground and canopy level thermal (A. – C.) and epithermal neutron intensity (D. – F.) plotted against measured and modeled: A. and D.) ground level thermal neutron intensity, B. and E.) ground level epithermal neutron intensity, and C. and F.) volumetric soil moisture.~~



~~Figure 16~~

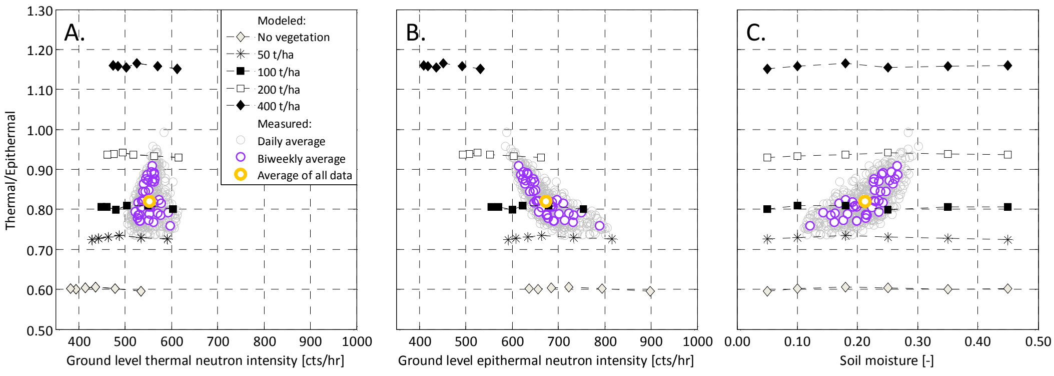


Figure 8 – Neutron intensities measured at Gludsted Plantation in the time period 2013-2015 and modeled using the Model *Tree trunk, Foliage, Air*. Ground level thermal-to-epithermal neutron intensity ratio plotted against measured and modeled: A.) ground level thermal neutron intensity, B.) ground level epithermal neutron intensity, and C.) volumetric soil moisture.

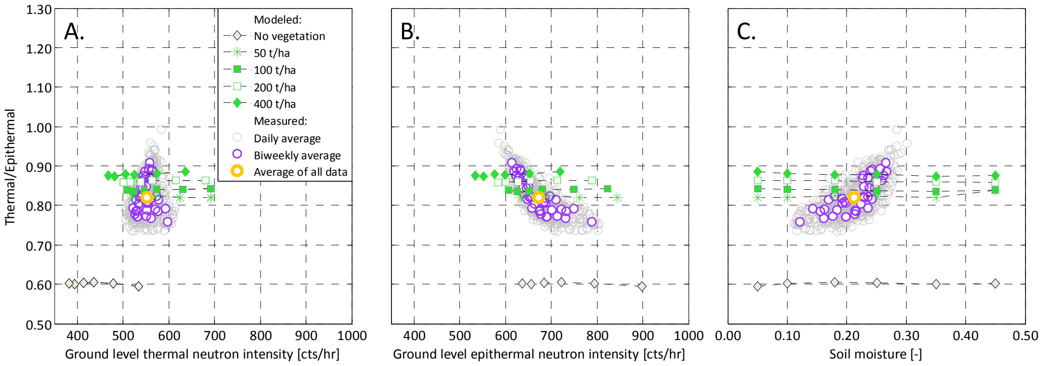


Figure ~~17~~9 – Neutron intensities measured at Gludsted Plantation in the time period 2013-2015 and modeled using the Model *Foliage*. Ground level thermal-to-epithermal neutron intensity ratio plotted against measured and modeled: A.) ground level thermal neutron intensity, B.) ground level epithermal neutron intensity, and C.) volumetric soil moisture.

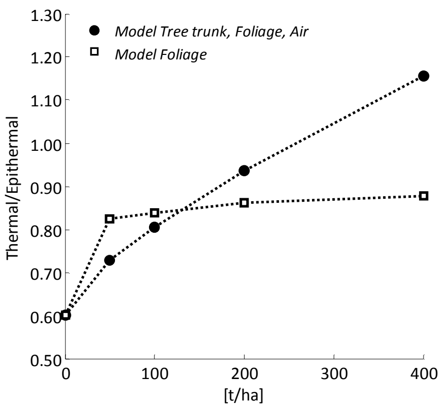


Figure 10 – Ground level thermal-to-epithermal neutron ratio plotted against biomass equivalent to dry above-ground biomass of: 50 t/ha, 100 t/ha (Gludsted Plantation), 200 t/ha and 400 t/ha using Model *Tree trunk, Foliage, Air* and Model *Foliage*, respectively.