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

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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).

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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 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

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. 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. 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 thermal and epithermal neutron intensity is also 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). Thereby, the thermal-to-epithermal neutron (t/e) ratio is 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.

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. Thus, the signal of canopy interception is within the measurement uncertainty, and cannot be identified at Gludsted Plantation using the available cosmic-ray neutron measurements.

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.

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). From ground level and up to an elevation of approximately 20 m the sensitivity to the amount of biomass on the neutron intensity is almost the same. From 20 m height, the sensitivity decreases with increasing elevation and for thermal neutrons the signal of biomass is almost gone at canopy level (not presented here). At canopy level, the sensitivity on epithermal neutrons is reduced, yet, a strong signal remains.

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.

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. 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

4. Discussions

4.1. Neutron height profile measurements and forest conceptualization

Slightly different neutron height profiles and t/e ratios were measured during the field campaigns in November 2013 and March 2014 (Figures 3-5). The area average soil moisture was similar for the two field campaigns, and the different neutron height profiles could therefore instead be a result of dissimilar soil moisture profiles or different soil moisture of the litter layer and the mineral soil. During two out of three soil sampling field campaigns different soil moisture of the litter layer and the mineral soil was observed at Gludsted Plantation (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)). Additional, the different neutron height profiles could also be a result of the different climate and weather conditions related to the seasons of detections (spring and fall). 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.

The neutron transport at the ground-atmosphere interface was found to be sensitive to the level of complexity of the forest canopy conceptualization, yet, the more appropriate conceptualization was not identified. 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 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.

4.2. The sensitivity on neutron intensity to soil chemistry and dry bulk density

In contrary to Gludsted Plantation, 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 litter at the forest floor and the forest biomass (not presented here). Accordingly, the effect of litter and mineral soil dry bulk density on neutron intensity is expected to be greater at non-vegetated field site. The reverse effect of increased dry bulk density of litter and mineral soil on neutron intensity is a result of the different elemental composition of the two materials. 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.

4.3. The potential of cosmic-ray neutron canopy interception detection

Ground level thermal neutron intensity was found to be sensitive to canopy interception, however, the signal is small and within the measurement uncertainty at Gludsted Plantation. 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 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.

4.4. The sensitivity to biomass on neutron intensity

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 using Model *Tree trunk, Foliage, Air*. 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. Applying Model *Foliage* both thermal and epithermal neutron intensity decreases with added amounts of biomass. The deviating behavior (compared to Model *Tree trunk, Foliage, Air*) may be due to the different elemental concentration of the forest canopy layers. Here, no space is occupied by a material of very low elemental density and may lead to an increased absorption of thermal neutrons.

The discrepancy of measured and modeled ground level t/e ratios (Figures 8 and 9) 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.

4.5. Cosmic-ray neutron biomass detection

The proposed possibility of estimating biomass at a hectometer scale using ground level t/e ratios was tested. The modeled ground level t/e ratio is compared with measurements of two additional field sites located 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, heathland and forest).

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.

Measuring ground-level t/e ratios for biomass estimation at a hectometer scale is promising as the measured ratio increases with increasing amounts of litter and biomass according to modeling. Still, ground level t/e ratio detection at locations of known biomass should be accomplished to test the suggested relationships. 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. 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). 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, cosmic-ray neutron intensity detection for biomass estimation at an intermediate scale is promising. Both the difference between ground and canopy level thermal and epithermal neutron intensity, respectively, and the ground level t/e ratios was found to increase 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. Additionally, 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)	4th order complexity	504*	257*	623*	717*
	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. 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

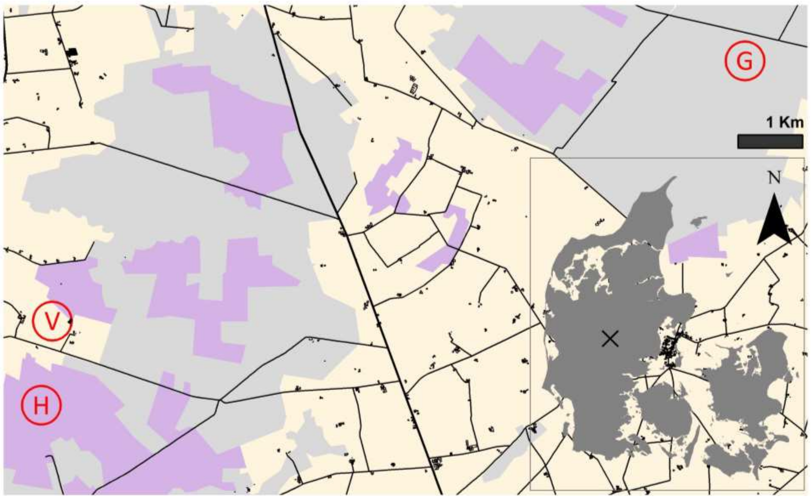

Figure 1 – Map showing the location of the three field sites; G: Gludsted Plantation (light gray), V: Voulund Farmland (beige) and H: Harrild Heathland (purple). The circles represent the footprint of the neutron detector (radius = 300 m).

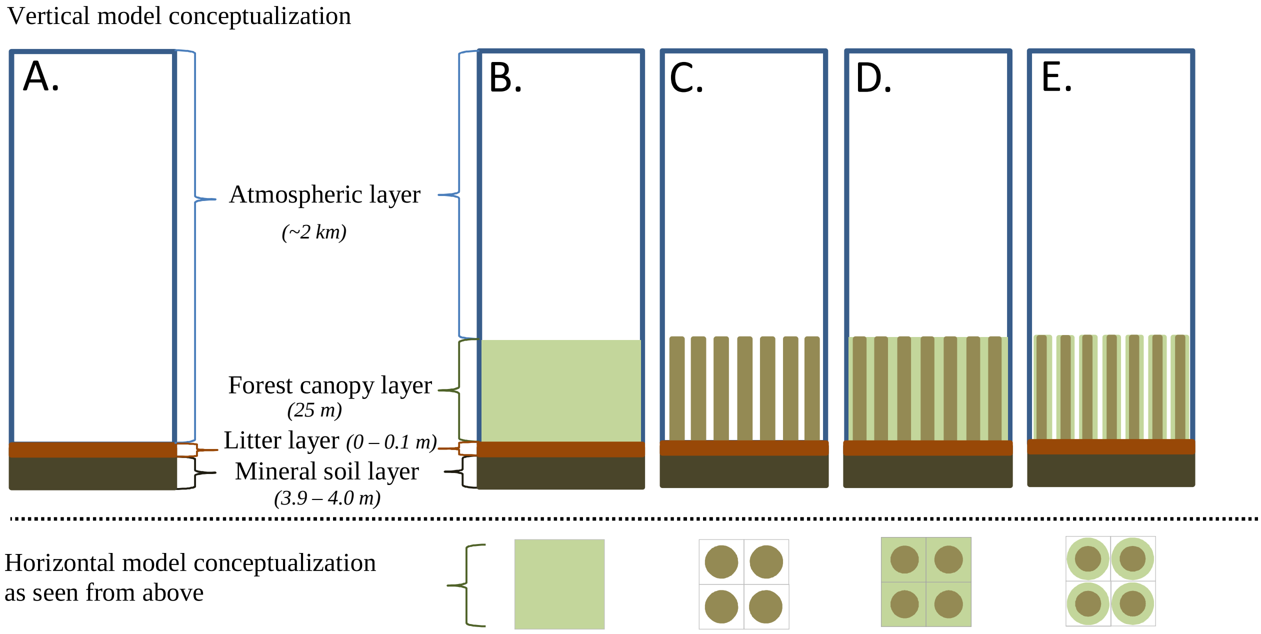

Figure 2 – Model conceptualizations of forest. A: no forest canopy layer (model name: *0 t ha*$^{-1}$); B: homogeneous foliage layer with a uniformly distributed biomass (model name: *Foliage*); C: cylindrical tree trunks with air in between (model name: *Tree trunks, Air*); D: cylindrical tree trunks with foliage in between (model name: *Tree Trunks, Foliage*); E:
5 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.

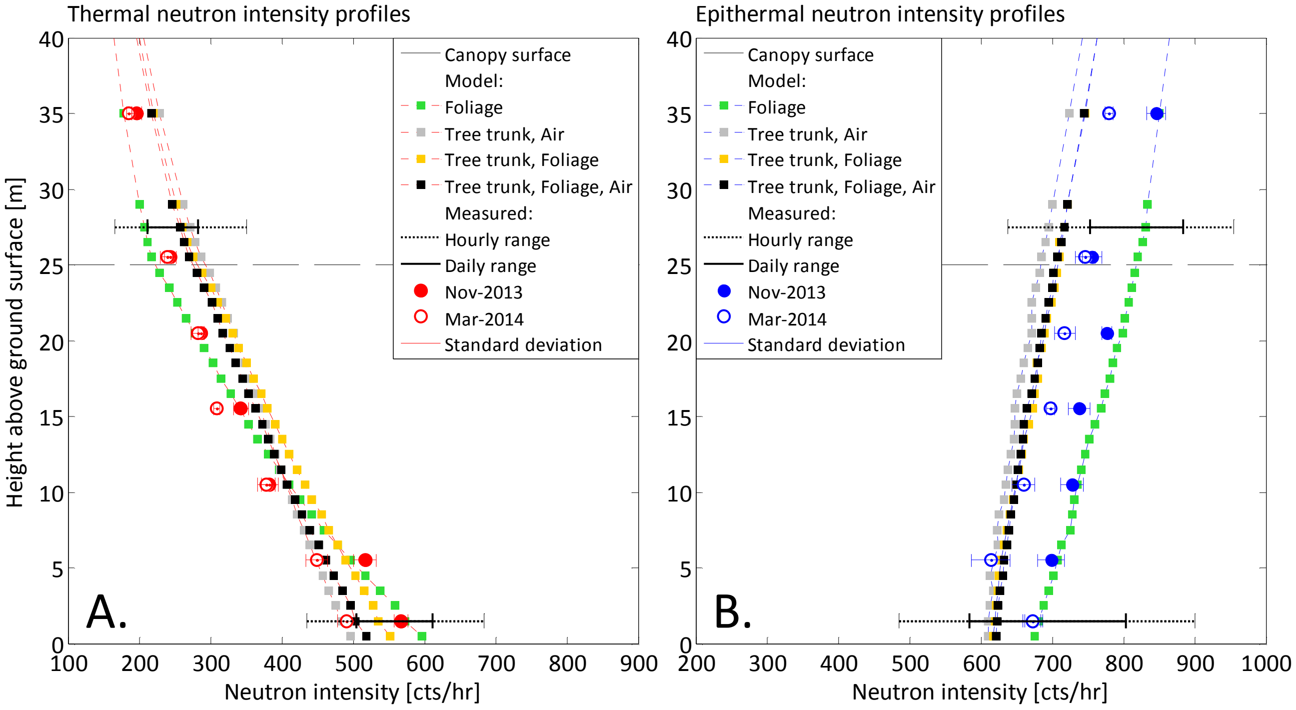

Figure 3 – Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015. Gludsted Plantation is modeled using four different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

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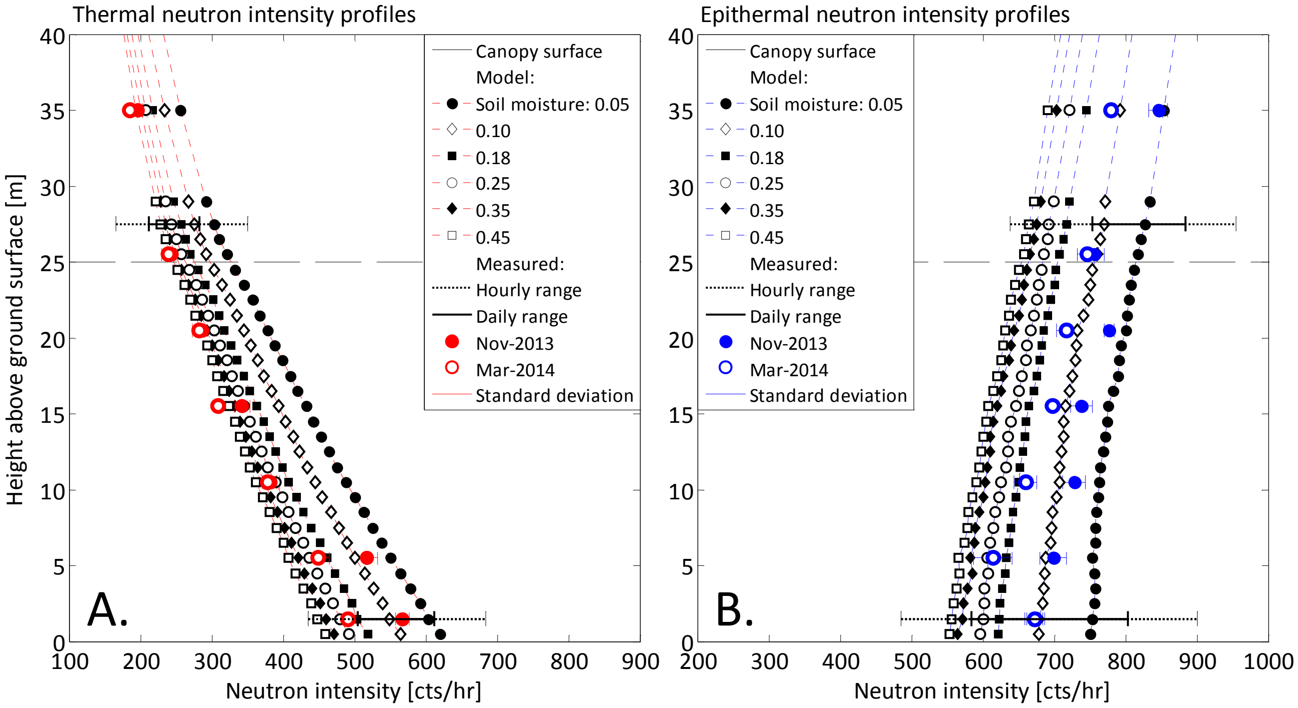

Figure 4 – Sensitivity to soil moisture (Model *Tree trunk*, *Foliage*, *Air*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the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

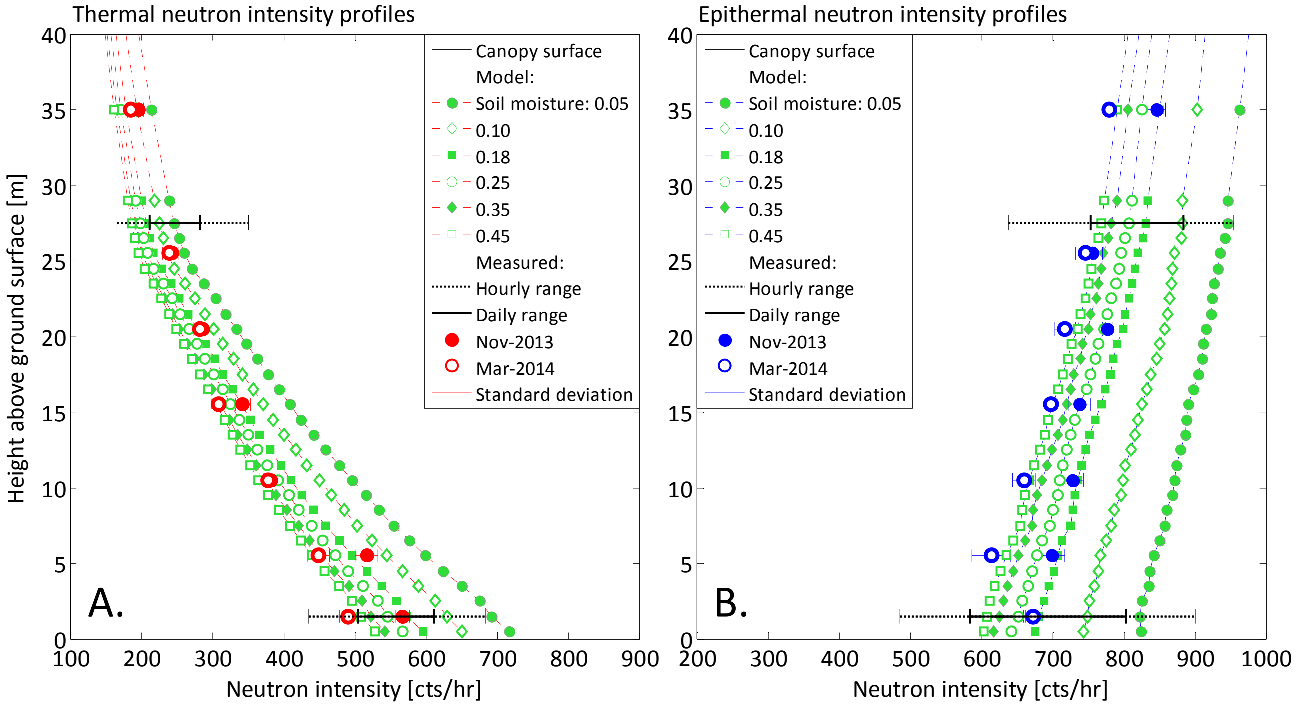

Figure 5 - Sensitivity to soil moisture (Model *Foliage*). Measured and modeled (A.) thermal and (B.) epithermal neutron intensity profiles at Gludsted Plantation. Hourly and daily ranges of variation of thermal and epithermal neutron intensities at ground and canopy level for the period 2013–2015.

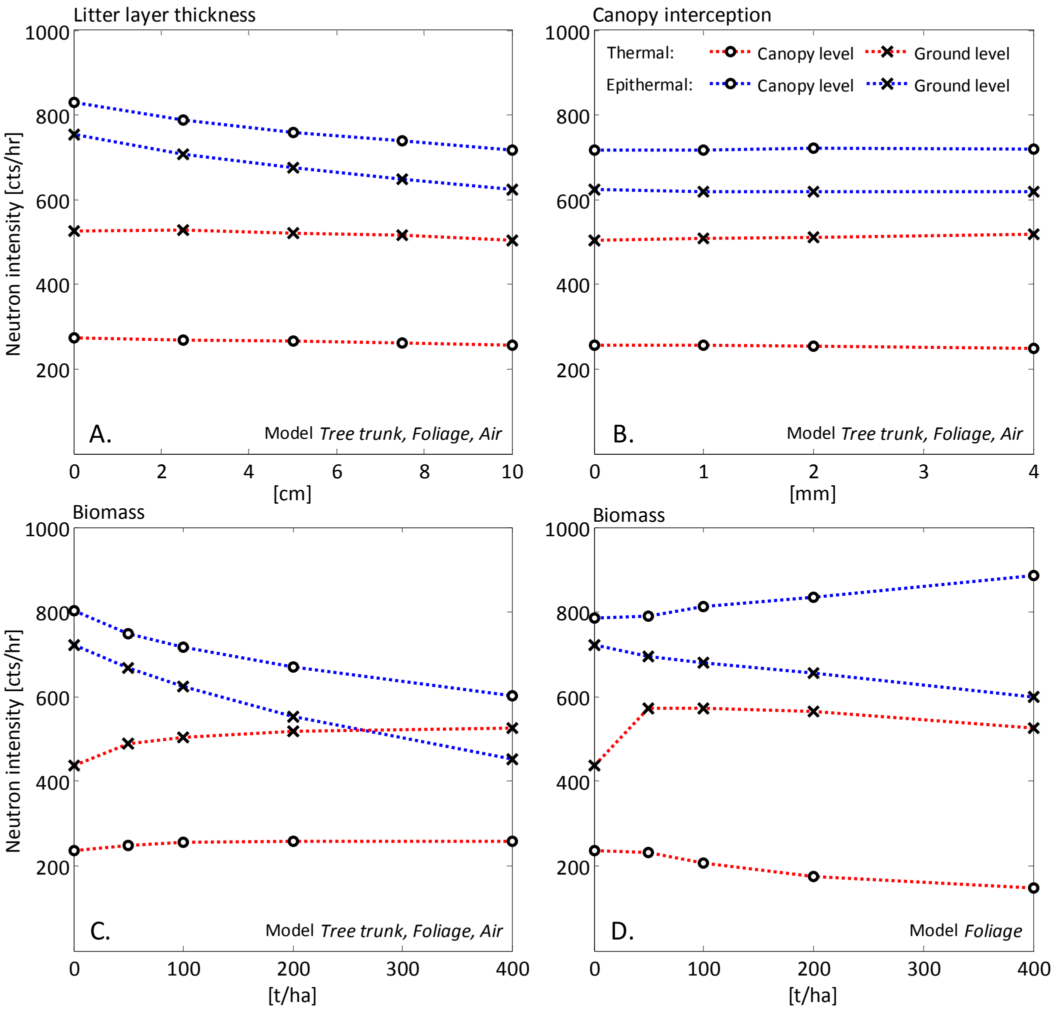

Figure 6 - Sensitivity to (A.) litter layer thickness using Model *Tree trunk, Foliage, Air,* (B.) canopy interception using Model *Tree trunk*, *Foliage*, *Air*, (C.) and D) biomass using Model *Tree trunk*, *Foliage*, *Air* and Model *Foliage*, respectively. Thermal and epithermal neutron intensity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

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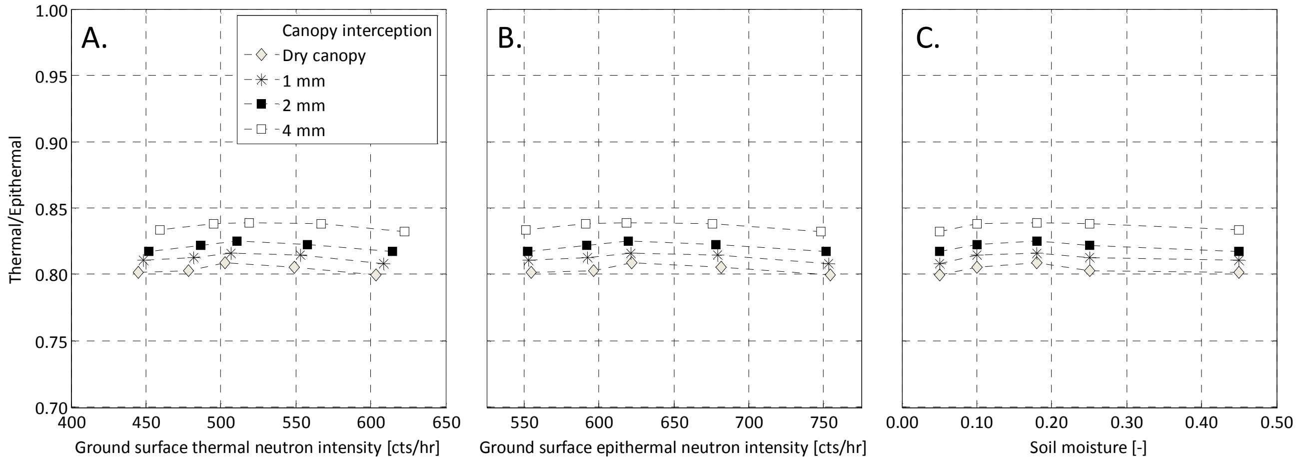

Figure 7 – Modeled ground level thermal-to-epithermal neutron intensity ratios using the Model *Tree trunk*, *Foliage*, *Air* for a dry forest canopy and canopy interception of 1 mm, 2 mm and 4 mm. plotted against modeled: A.) ground level thermal neutron intensity, B.) ground level epithermal neutron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

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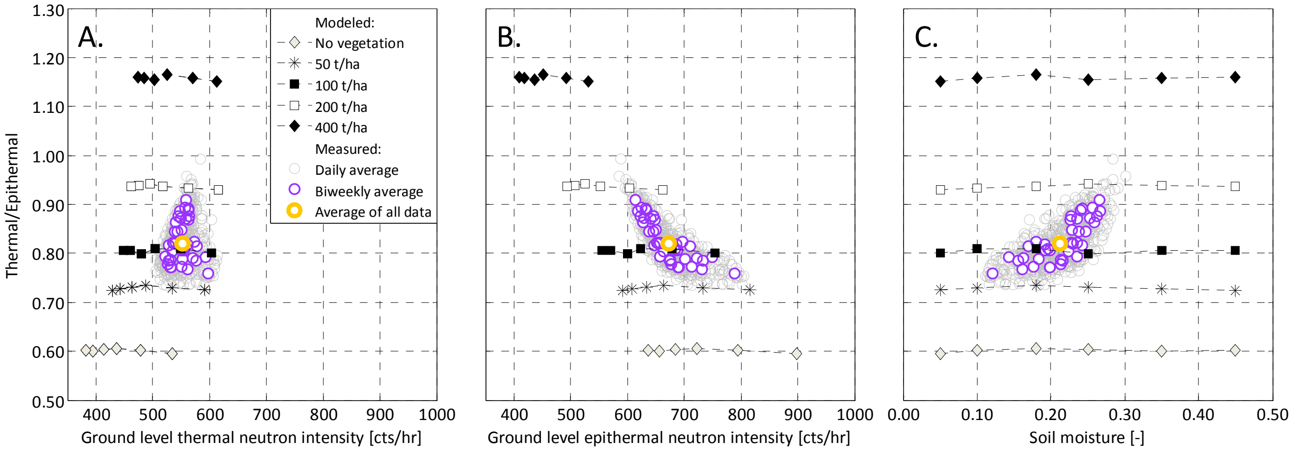

Figure 8 – Neutron intensities measured at Gludsted Plantation in the time period 2013-2015 and modeled using the Model *Tree trunk*, *Foliage*, *Air*. Ground level thermal-to-epithermal neutron intensity ratio plotted against measured and modeled: A.) ground level thermal neutron intensity, B.) ground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

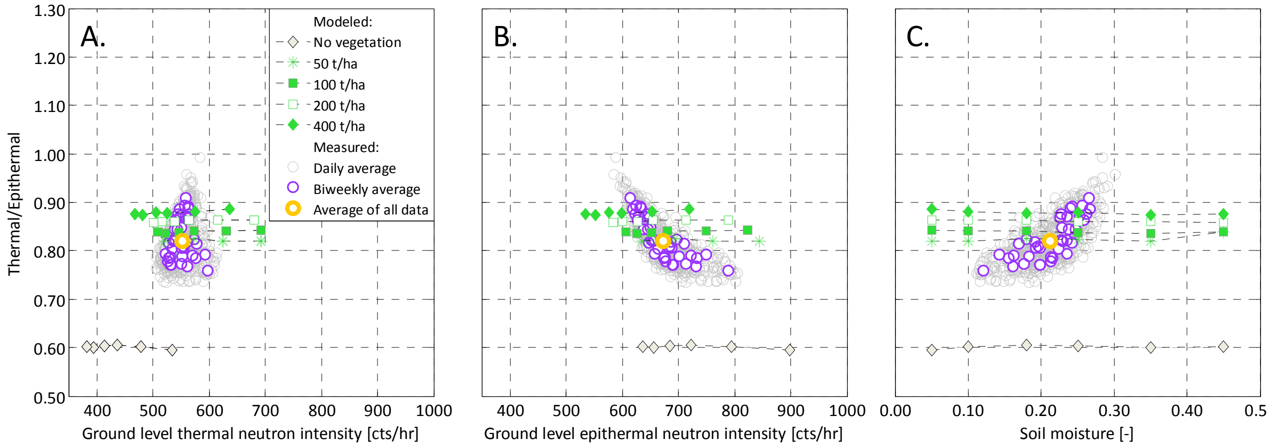

Figure 9 – Neutron intensities measured at Gludsted Plantation in the time period 2013-2015 and modeled using the Model *Foliage*. Ground level thermal-to-epithermal neutron intensity ratio plotted against measured and modeled: A.) ground level thermal neutron intensity, B.) ground level epithermal neutron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

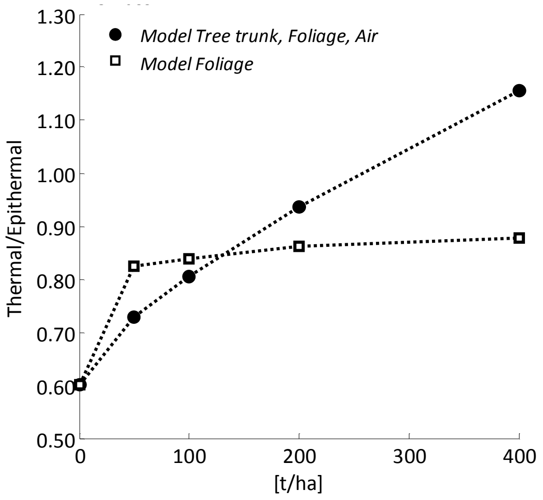

Figure 10 – Ground level thermal-to-epithermal neutron ratio plotted against biomass equivalent to dry above-ground biomass of: 50 t/ha, 100 t/ha (Gludsted Plantation), 200 t/ha and 400 t/ha using Model *Tree trunk, Foliage, Air* and Model *Foliage*, respectively.