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A scaling approach for the assessment of biomass changes and rainfall interception using cosmic-ray neutron sensing

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SUMMARY

Cosmic-Ray neutron sensing (CRS) is a unique approach to measure soil moisture at field scale filling the gap of current methodologies. However, CRS signal is affected by all the hydrogen pools on the land surface and understanding their relative importance plays an important role for the application of the method e.g., validation of remote sensing products and data assimilation. In this study, a soil moisture scaling approach is proposed to estimate directly the correct CRS soil moisture based on the soil moisture profile measured at least in one position within the field. The approach has the advantage to avoid the need to introduce one correction for each hydrogen contribution and to estimate indirectly all the related time-varying hydrogen pools. Based on the data collected in three crop seasons, the scaling approach shows its ability to identify and to quantify the seasonal biomass water equivalent. Additionally, the analysis conducted at sub-daily time resolution is able to quantify the daily vertical redistribution of the water biomass and the rainfall interception, showing promising applications of the CRS method also for these types of measurements. Overall, the study underlines how not only soil moisture but all the specific hydrological processes in the soil-plant-atmosphere continuum should be considered for a proper evaluation of the CRS signal. For this scope, the scaling approach reveals to be a simple and pragmatic analysis that can be easily extended to other experimental sites.

1. Introduction

Soil moisture is a key variable of the water cycle influencing land-atmosphere interactions and impacting rainfall-runoff processes (e.g., Bronstert et al., 2011; Vereecken et al., 2008). It shows strong variability at different spatial and temporal scales and its characterization is still an important challenge within the hydrological sciences (Corradini, 2014). In the last decades, several methods were developed to measure this variable. The methods can be divided in contact-based point scale measurements (Romano, 2014), proximal soil sensing techniques (Vereecken et al., 2014) and remote sensing approaches (Fang and Lakshmi, 2014). In this context, Cosmic-Ray neutron Sensing – CRS (Zreda et al., 2008) proved to be a promising proximal soil sensing technique to measure soil moisture at field scale and fill the gap of current methodologies (Robinson et al., 2008).

CRS is based on the well-known interaction between neutrons and hydrogen that is used for many applications (Gardner and Kirkham, 1952; Oswald et al., 2008; Waring et al., 2011). However, the instrument measures the background neutrons emitted naturally from soil that are created by secondary Cosmic-Ray fluxes coming in through the atmosphere (Zreda et al., 2012). Avoiding the use of an active source of neutrons, this method can be applied in several field conditions without the limitations encountered by other neutron-hydrogen methods e.g., by the conventional downhole neutron scattering technique for soil moisture measurements.

The first attempt on the measurements of this natural background neutrons for hydrological applications has been presented by Kodama et al. (1979). In this study a neutron detector was installed below ground and the signal was found to be well correlated with both soil moisture and snow water equivalent. However, with this set up, the signal was strongly related to the hydrogen pools close to the probe without particular advantages in comparison to other soil moisture techniques (e.g., TDR). Nevertheless, this study is noteworthy given the applications of it to measurements of snow and current use as a monitoring network over France (Morin et al., 2012).

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More recently, Zreda et al. (2008) tested the use of a specific neutron detector installed above-ground. Based on using neutron transport simulations and field measurements, the authors proved that with this set up the CRS signal represents the land surface within a footprint of 300 m radius in space and a depth between 10 and 70 cm. Additionally, they showed that with a specific neutron energy level the signal was less sensitive to the parental materials i.e., soil type. In such a way, this study put CRS in a new perspective proving to be a valuable and unique technique to measure soil moisture at an intermediate scale and showing to be a promising method with a range of applications.

After this first result, several studies have been conducted to test and to increase the applicability of the CRS method. Initially, a nonlinear calibration function that relates average soil water content to neutron counts has been suggested (Desilets et al., 2010). This calibration function is based on the assumption that static background hydrogen sources are implicitly accounted for in the local calibration. Subsequently, a universal calibration function has been presented in case all hydrogen pools are explicitly considered (Franz et al., 2013a). Recently, the local calibration function has been slightly modified to explicitly acknowledge the presence of additional static hydrogen pools (Dong et al., 2014; Hawdon et al., 2014). Additionally, a modification of the universal calibration function has been proposed (McJannet et al., 2014). Moreover, a relatively simple operator (COSMIC) has been developed to overcome the complexity of the Monte Carlo neutron particle simulation model (MCNPX) and to provide the basis for the use of CRS in comparison to hydrological models and data assimilation (Rosolem et al., 2014; Shuttleworth et al., 2013).

Independently from the functional relation used, the calibration is usually conducted collecting soil samples in the support volume (Baatz et al., 2014). A standard sampling scheme is proposed to account for the spatial sensitivity of the signal and a good estimation of the average soil moisture in the field (Franz et al., 2012b). This sampling scheme showed good accuracy in case the soil spatial variability within the footprint is affected by relatively short correlation length. However, it was also suggested that adaptation of the soil sampling scheme may be needed when water management conditions (e.g., irrigation strips) or other natural conditions create spatial structures with longer correlation length.

Based on these assumptions, CRS showed good soil moisture estimation (RMSE < 2%) in comparison with a network of local soil moisture measurements (Franz et al., 2012b). A static network of Cosmic-Ray neutrons sensing probes was then established (Zreda et al., 2012) and is continuing to increase all over the world (Baatz et al., 2014; Hawdon et al., 2014). Moreover, measurements have been obtained in a roving set up covering an area of several square kilometers, making of this method a valuable approach also in larger scale soil moisture monitoring (Ochsner et al., 2013) and for the validation of remote sensing products (Chrisman and Zreda, 2013; Dong et al., 2014).

However, some limitations with the use of CRS for soil moisture measurements have been found in specific field conditions. A first limitation occurred because the neutrons are correlated to all the hydrogen pools in the footprint. The hydrogen is present not only in the soil moisture but also in different compartments, such as above- and below-ground biomass, humidity of the lower atmosphere, lattice water of the soil minerals, litter layer, intercepted water in the canopy and soil organic matter. Limitation in the applicability of the CRS method arises in case the soil moisture is not a dominant fraction of these hydrogen pools. In these conditions the sensitivity of the CRS decreases and the accuracy of the measurements could be relatively low. Bogena et al. (2013) showed for example that, in a wet forest site, soil moisture was a relatively small contribution of the total hydrogen pool and the RMSE calculated in comparison to a soil moisture network installed in the footprint of the CRS was relatively high (RMSE 3%). To overcome this first limitation, it is possible to increase the integration time of the neutron counts (e.g., daily, weekly), sacrificing, however, time resolution of the measurements. Additionally, a more sensitive neutron detector can be used, as it was for example considered in the application of the CRS in the roving set up (Chrisman and Zreda, 2013; Dong et al., 2014).

A second limitation using CRS for soil moisture measurements occurred because some hydrogen pools are approximately static (e.g., lattice water, soil organic carbon) but other hydrogen pools are time-varying (e.g., interception of the canopy, water content of the litter layer, biomass water). The static background hydrogen sources could be implicitly or explicitly accounted for in the calibration (Franz et al., 2013a, 2012b). However, in case more than one hydrogen source is time-varying, an additional correction to separate the different contributions on the CRS signal should be adopted. Rosolem et al. (2013) showed, for example, the effect of the atmospheric water vapor on the signal detected. Consequently, they introduced an empirical correction that is now a standard preprocessing of the neutron counts. Bogena et al. (2013) showed the importance of the little layer at a humid forest site. In this specific case, due to the lack of direct measurements, the correction was introduced based on modeling results. Hornbuckle et al. (2012) and Rivera Villarreyes et al. (2011) found that biomass growth affected considerably the CRS signal. The studies underlined the limitations in the applicability of the CRS for soil moisture measurements in particular in agricultural field where fast (i.e., seasonal) biomass growth is expected. Similarly, Hawdon et al. (2014) and Baatz et al. (2014) showed that biomass can explain the variation in calibration results conducted in experimental sites with different land use. It is also worth to mention that studies on the effect of other second time-varying hydrogen pools are missing (e.g., rainfall interception, snow).

For these reasons, the objective of this study is to evaluate the role of different time-varying hydrogen contributions on the CRS signal. In particular, the study focuses on biomass and rainfall interception that play an important role in the specific experimental site i.e., cropped field. To this end, a scaling approach based on soil moisture measurements is used to overcome the need to measure each hydrogen contribution. The methodology is evaluated in detail with the data collected in one cropped season and a longer term application with two different land uses is presented.

2. Materials and methods

2.1. Experimental site and measurements

Field measurements and monitoring activities were carried out in a relatively flat and homogenous cropped field of about 30 ha in Bornim (Brandenburg, Germany) (Fig. 1). The area, situated 40 m a.s.l., is characterized by mean annual precipitation of 595 mm and minimum and maximum daily values of 15 °C (February) and 30 °C (July), respectively (Meteorological Station Potsdam Telegrafenberg, Germany). Soil texture of the site was reported to be dominated up to 1 m by 75% sand content, 17% silt content and 8% clay content (Gebbers et al., 2009) referring to a loamy-sand soil classification (USDA). The groundwater level is about 5 m below the surface as suggested by information from the State Environmental Agency based on a groundwater well nearby.

The field was equipped with CRS probes since 2010 and different measurements were conducted for comparison (Rivera Villarreyes et al., 2014, 2013, 2011). Data collected during three different cropped seasons are analysed in the present study: sunflower, winter rye and maize, respectively. The CRS probe was installed in the center of the experimental site covering with its