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Integral quantification of seasonal soil moisture changes in farmland by cosmic-ray neutrons

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Abstract

The measurement of soil moisture at the plot or hill-slope scale is an important link between local vadose zone hydrology and catchment hydrology. However, so far only a few methods are on the way to close this gap between point measurements and remote sensing. One method that could determine an integral soil moisture at this scale is the so called cosmic ray sensing that was introduced to soil hydrology very recently the first time. The present study performed cosmic ray sensing at an agricultural field in a Central European lowland. To test the method it was accompanied by other soil moisture measurements for a summer period with corn crops growing on the field and a later autumn-winter period without crops and a longer period of snow cover. Additionally, meteorological data and above-ground crop biomass was included into the evaluation. Hourly values of cosmic ray sensing showed a high statistical variability. Six-hourly values corresponded well with classical soil moisture measurements, after calibration based on one dry and three wet periods of a few days each. Crop biomass seemed to influence the measurements only to minor degree, opposed to snow cover which has a more substantial impact on the measurements. The latter could be quantitatively related to count rates in two different variants of cosmic ray counters. Overall, our study outlines a procedure to apply the cosmic ray sensing method based on devices now commercially available, without the need for accompanying numerical simulations and suited for longer monitoring periods after initial calibration.

1 Introduction

Soil moisture plays an important role in the hydrological cycle. It influences climate and weather (Wu and Dickinson, 2004), and also determines surface runoff after precipitation events and controls groundwater recharge. More than that, in its own right it is a key factor in soil for chemistry, biology, infiltration and matter transport, e.g. it provides the plant-available pool of water for vegetative life on the planet (Robinson et al., 2008).

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Despite the importance of soil moisture, its representative measurement is still a big challenge in hydrological research. Progress in observation techniques of soil moisture has improved at various scales. Measurements of soil moisture at the point-scale (∼1 dm^3) have advanced significantly in the last decades for a wide range of sensors. These are usually the basis for calculation of water storage and its changes at the field scale (up to 1 km^2). Point measurements are scaled up to large areas applying several geostatistical techniques to interpolate and extrapolate values (Western et al., 2002). However, inherent small-scale soil heterogeneities and non-linearity of processes dominate spatial and temporal variability of soil moisture and introduce sources of error that can produce significant misinterpretation of hydrological scenarios and unrealistic predictions. At the basin scale (2500–25 000 km^2), remote sensing technology, both active and passive, has demonstrated the potential to map and monitor surface soil moisture changes over large areas at regular intervals in time (Barrett et al., 2009). Satellites with L-band radiometers, e.g. *SMOS* (Kerr et al., 2001), and the planned *SMAP* mission (Entekhabi et al., 2010), or gravity change detection, *GRACE* (Tapley et al., 2004), provide a spaceborne Earth observation with opportunities to estimate soil moisture at the continental scale.

Although the great promising of these techniques for practical applications, current measurement capabilities still do not cover the crucial need of hydrological observations corresponding to soil moisture in the root zone at the scale of a field, a small watershed scale or a hydrologic response unit. New measurement methods of soil moisture are investigated to obtain more information on this intermediate scale gap, e.g., spatial TDR soil moisture measurements (Graeff et al., 2010), ground penetrating radar (GPR) measurements (Huisman et al., 2003), electrical resistivity tomography (ERT) measurements (Garre et al., 2011), or ground-based microwave radiometer (Schwank et al., 2009). In practice, these techniques are limited to the estimation of soil moisture at the very surface, influenced by soil chemistry, hindered by vegetation-cover, and limited in temporal or spatial coverage. In general, there are either invasive methods that can detect also deeper soil moisture, but in a point-like manner, or non-invasive or remote sensing methods with high spatial coverage but representing shallow soil only. Ground penetrating radar can do a deeper assessment non-invasively, but it is costly and only an indirect measurement.

Recently two novel methods were introduced that potentially can fill the gap of soil moisture measurements at the field scale, the so called cosmic ray method (Zreda et al., 2008) and measuring water storage changes by a high-precision gravimeter (Creutzfeldt et al., 2010). While both are non-invasive and detect water storage changes in a similar integration area, called footprint or support scale, the gravimeter is less mobile and its measurement includes also water stored in shallow groundwater (Christiansen et al., 2011; Leirião et al., 2009); and thus an estimation of soil moisture itself is more complicated. We will focus here on the former novel method performed via an above ground cosmic ray sensor (CRS), which effectively counts neutrons generated in soil by incoming cosmic rays.

In Zreda et al. (2008) and Desilets et al. (2010) it was shown by simulations that natural fast neutrons, generated primarily by interactions of secondary cosmic-ray neutrons with terrestrial and atmospheric nuclei, are inversely correlated to soil moisture at an integration area, called footprint, with a diameter up to 600 m (at sea level). The penetration depth of the measurement by the CRS, taken as the depth up to which a relevant part of counted neutrons originates from, ranges up to 1.0 m. The method is based on the crucial role of hydrogen as neutron moderator due to its total scattering cross sections (82.02 barn) compared to others elements present in parents rocks (e.g. 2.167 barn for Si, see Table 1) (Sears, 1992).

Neutrons at the air/ground interface are moderated by any chemical and physical form of hydrogen ^{1}H in or above soil surface, e.g. soil moisture, snow water, intercept water, biomass water, and also carbohydrates. Therefore, there is still an open question if the non-invasive cosmic ray method is suitable to quantify water stored in environmental compartments at the field scale.

At the lab scale, the interaction of neutrons in the thermal to cold range has become a valuable tool to investigate water distributions, also in soil-plant systems (e.g. Oswald et al., 2008; Tumlinson et al., 2008). This imaging technique with neutrons can provide 2-D and 3-D maps of soil moisture with high spatial resolution and time intervals of minutes to hours. So it can be used to study water redistribution dynamics and plant water uptake on scale of a single plant in detail. Whereas for this neutron imaging a large, intensive and parallel beam of neutrons has to be generated at special facilities and 2D detectors are required, the cosmic ray sensing works with the natural, low background of neutrons and a detector that does not provide a spatial resolution. In a way this can be seen as an analogue to the method pair of magnetic resonance imaging in lab devices producing high magnetic fields and geophysical surface nuclear magnetic resonance based on the weak Earth's magnetic field.

In this manuscript, we present a study of cosmic-ray neutrons for the estimation of soil moisture at an agricultural site in Germany. We quantified the relative influence of crop biomass in a summer period and investigated the impact of snow during a fall-winter period. This is to our knowledge the first investigation of this kind outside the USA reported in literature, and also the first in an agricultural field. This study has been designed to:

- extend the first applications of the cosmic ray method to a different geographical context,
- monitor cosmic-ray neutrons under two different vegetative situations (cropped field and bare soil) and different seasonal conditions (summer and winter),
- measure temporal variability of water mass in the air/ground interface and to evaluate the effective response of the cosmic ray method to hydrological events.

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2 Materials and methods

2.1 Basis of the cosmic ray method to detect soil moisture

High energy cosmic rays mostly consist of charged protons. The major attraction of these primary cosmic rays is carried out in the top atmosphere by Earth's magnetic field. Since there is a spatial variability of Earth's magnetic field along the globe, e.g. with latitude, incoming high energy cosmic rays vary for different locations. Besides that, the incoming cosmic rays depend in astronomic processes such as solar modulation (Parker, 1965). However, this variability will be neglected here because it is mainly a longer term modulation.

In the atmosphere, incoming protons generate a cascade of secondary cosmic rays as product of their collision with atmospheric nuclei (Lal and Peters, 1967). Here, the intensity of this secondary cascade is related to how much air mass was encountered during the transit through the overlying atmosphere. Therefore, variations of air pressure affect intensity of secondary cosmic ray fluxes.

Once the secondary cascades of cosmic rays arrive at the ground level, these collide with the land surface as a much denser medium, where lower energy neutrons are created as product of these new interactions between soil and secondary cosmic rays. Cosmic-ray neutrons in the intermediate energy level (1–2 MeV), so called fast neutrons (Hess et al., 1961), might reach the soil-surface and thus free air after scattering in the soil. Neutrons are moderated, i.e. lose kinetic energy through several collisions with surrounding nuclei in the soil on the way out to atmosphere, others are even completely absorbed by the soil.

Hydrogen plays an important role in this neutron attenuation of thermal to fast neutrons. For example, a fast neutron only requires 26 collisions with hydrogen nuclei to decrease its energy from 2 MeV (fast level) to 0.025 eV (thermal level), compared to other common elements such as C (119 collisions), O (155 collisions), N (137 collisions), Al (255 collisions), Si (265 collisions), etc. (Table 1). In conclusion, water molecules, namely ^{1}H and ^{16}O, are a key factor to moderate these neutrons and thus the intensity of neutrons above strongly depends on the water mass present in soil. This allows a non-invasive estimation of soil moisture.

2.2 Quantitative soil moisture estimation by cosmic-ray neutron measurements

Neutrons can be detected by special counters. They count events resulting from neutrons passing the detector during a preset integration period. Based on modeling studies an equation was proposed by Desilets et al. (2010) that could be used to relate neutron flux and soil moisture. We suggest working with a slightly modified version of this, as in the following. Overall, we suggest a modified procedure to ease the practical application of the method without the need of modeling neutron transport. The equation for the estimation of the soil moisture is as follows:

$$\theta = \frac{a_o}{(N_\mathrm{R} - a_1)} - a_2 \tag{1}$$

where θ is the volumetric areal mean soil moisture, N_R is the normalized and pressure-corrected neutron counting rate (specified in Eq. 3), and a_i are fitting parameters.

The intensity of cosmic rays reaching the land surface fluctuates with changes in the mass density of the atmosphere, i.e. actually atmospheric pressure. Thus, neutron counting rates can be corrected by accounting for fluctuations of atmospheric pressure as follows

$$N = N_\mathrm{raw} \cdot \exp\left[\beta(P - P_\mathrm{mean})\right], \tag{2}$$

where N_raw is fast neutron counting rate integrated in a fixed time period, β is the atmospheric attenuation coefficient for cosmic rays, P is the local pressure corresponding to period when N_raw was observed and P_mean is the long-term mean local pressure.

The integration period of cosmic-ray neutrons depends on desired accuracy of estimations of soil moisture. Events of neutron counting rates follow mainly a Poissoinian statistical distribution which suggests that the standard deviation of neutrons counted in a fixed interval is equal to its square root. The range of neutron counting rates depends on several variables (e.g. site location, fluctuation of incoming protons due to solar activity changes, and other types of moderation such as biomass or open water bodies in the direct proximity), where site altitude usually is the predominant one. Neutron counting rates are lower in altitudes near to sea level compared to mountain altitudes; therefore, estimations of soil moisture require longer integration periods of neutron counts at lower altitudes.

Based on Eq. (2), the normalized and pressure-corrected neutron counting rate (N_{R}) is defined as

$$N_{\mathrm{R}} = \frac{N_{\mathrm{raw}} \cdot \exp\left[\beta\left(P - P_{\mathrm{mean}}\right)\right]}{N_{\mathrm{dry\_raw}} \cdot \exp\left[\beta\left(P_{\mathrm{dry}} - P_{\mathrm{mean}}\right)\right]} \tag{3}$$

and this can be simplified to

$$N_{\mathrm{R}} = \frac{N_{\mathrm{raw}}}{N_{\mathrm{dry\_raw}}} \cdot \exp\left[\beta\left(P - P_{\mathrm{dry}}\right)\right], \tag{4}$$

where $N_{\mathrm{dry\_raw}}$ is the fast neutrons counting rate measured under dry soil conditions and P_{dry} is the local pressure corresponding to dry condition where $N_{\mathrm{dry\_raw}}$ was observed. The attenuation coefficient (β) for neutron fluctuations induced by local air pressure was calculated from historical data of cosmic-ray neutrons and air pressure from four neutron monitoring stations.

The second type of corrections of neutron counting rates in the air/ground interface is due to variations of high energy primary cosmic rays. Existing databases of neutron monitoring worldwide stations (http://www.nmdb.eu/) observe spatial variations and temporal fluctuations of incoming cosmic ray. Four most proximal stations KIEL (Kiel, Germany), LMKS (Lomnicky stit, Slovakia), JUNG (Jungfraujoch, Switzerland) and ROME (Rome, Italy) were selected to obtain hourly changes of neutron counting rates exclusively due to fluctuations of incoming high energy cosmic rays. Time series of hourly neutron counts were normalized to the maximum value observed in each station during the selected period. Normalized neutron fluxes in all these stations were quite similar despite different detection sensitivities, e.g. different neutron detectors. Our analysis showed that incoming cosmic ray did not drastically vary during our observation period. Therefore, we assumed that a correction of neutron counting rates by variability of incoming primary cosmic rays is not necessary.

2.3 Horizontal and vertical coverage of cosmic ray method

Horizontal spatial coverage of the cosmic ray method can be defined as the region within which 86 % of the counted neutrons are originated (Zreda et al., 2008). Since cosmic-ray neutrons depend on atmospheric pressure, also the so called footprint is inversely proportional to atmospheric pressure. Probability of nuclei collisions in air are significantly less than in soil, hydrogen moderation is higher in soil moisture than air humidity. Therefore, neutron counting rate observed in a particular location is a measurement of neutrons originally released from the soil in a considerable distance away from the detector (Shuttleworth et al., 2010). By means of simulations, Zreda et al. (2008) suggested a 600-m diameter footprint at the sea level.

The vertical coverage of the cosmic ray method depends on soil moisture, because the probability of neutron scattering and absorption events depends on the number of hydrogen molecules. Hydrogen has higher scattering cross section compared to typical rock chemical constituents. Numerical simulations by the Monte Carlo Neutron Particle (MCNP) transport code (Briesmeister, 1997) suggest in silica matrix a vertical coverage by neutrons counted above ground ranging from about 0.8 m in dry soils to 0.1 m in wet soils (Zreda et al., 2008). An analytical expression for the moderated mean free path $\overline{\lambda_m}$ [m] of neutrons produced by cosmic rays in soil can be given as follows

$$\overline{\lambda_m} = \frac{1}{\theta(\Sigma)_{\text{water}} + (1-n)(\Sigma)_{\text{soil}} + (n-\theta)(\Sigma)_{\text{air}}} \tag{5}$$

where θ is volumetric soil moisture [$\text{m}^3\,\text{m}^{-3}$], n is soil porosity [–], and Σ_i is the attenuation coefficient for material i (water, soil or air) [cm^{-1}]. The moderated mean free path is an indicator of the soil depth from which neutrons can be detected assuming homogenous soil chemical characteristics under variable-saturation conditions (neutron moderation by air in void volume). It depends not only on the type of material but also on the energy of the neutron penetrating the medium, because their total macroscopic cross section changes with neutron energy.

However, if only epithermal to fast neutrons are counted by a CRS, the mean free path depends only weakly on the chemical composition of the soil, as shown by Zreda et al. (2008). Therefore, a count of neutrons in this energy range will predominantly depend on water content, but only to minor degree on soil composition. And worth mentioning, the neutrons detected in the sensor come from a broad range of angles, including almost horizontal ones. The reason is that the mean free path in air is typically in the order of tens of meters, and the counting probability usually does not strongly depend on the angle. This is also the reason why the exact height of a CRS above ground surface is not sensitively influencing counting rates as long as it is not shielded by surface structures and is lower than the mean free path in air.

2.4 Experimental site

The non-invasive cosmic ray method for estimation of soil moisture was tested in a 30-ha agricultural field in Bornim (Brandenburg, Germany). The test site is located close to Potsdam, and 30 km west of Berlin (Fig. 1). The landscape at the site was formed by the last ice age. Soil texture of the site was reported to be dominated down to 1 m by 75 % sand content, 17.2 % silt content and 7.8 % clay content (Gebbers et al., 2009). Texture analysis was done for a number of samples from this field site in Bornim, and a loamy sand type is predominant in all 19 selected sampling locations (Fig. 1). Percentages of sand (between 77.8 and 86.2 %), silt (between 8 and 14.8 %) and clay (between 4.8 and 9.4 %) always indicated this soil classification, in agreement with the previous work in the area (Gebbers et al., 2009).

In terms of climate conditions, the period of highest precipitation is between May and August. Total mean annual precipitation in last 50 yr was 595 mm. Maximum values of

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relative humidity are in months of November, December and January, reaching values up to 94 %. Historical data of air temperature shows minimum and maximum values of −15.43 °C (February) and 30.30 °C (July), respectively, in the last hundred years (Meteorological Station Potsdam Telegrafenberg – Germany).

At the field site, the monitoring period started at 27 August 2010 when the field was cropped with corn (*Zea Mays*). The monitoring continued until corn was harvested on 14 September 2010. A second monitoring period was again started on 26 November 2010 in a condition of bare soil and continued until the end of March 2011. Thus, the first period covered a part of late summer and the second period covered the transition from late autumn to winter to even the beginning of spring. Weather data was provided from the nearby station of Leibniz Institute for Agricultural Engineering Potsdam-Bornim, located about 1 km from the experimental field. Snow fall data was taken from the Meteorological Station Potsdam Telegrafenberg located about 6 km East of the site.

2.5 Biomass and cosmic ray method

The role of biomass on estimations of soil moisture by means of the cosmic ray method is open to discussion. The presence aboveground biomass could affect the cosmic-ray neutrons in two ways: (1) the biomass produces moderating effects on incoming cosmic rays and on neutrons from soil before they reach the detector, mainly by its water content, and (2) scattering and absorption properties of other biomass constituents (e.g. carbohydrates) also reduce neutron fluxes at the ground/air interface. For example, the biomass of a temperate rain forest can moderate 4.7 ± 2.3 % of incoming cosmic ray neutrons (Plug et al., 2007). It can be expected that vegetation with lower biomass will have a less important influence on incoming cosmic rays and secondary neutrons emanating from soil.

In order to understand the influence of biomass on the cosmic ray method, spatial and temporal variability of corn was monitored. Two field campaigns (19 August 2010 and 6 September 2010) were done to measure the crop height for a total of 96 points according to the sampling grid shown in Fig. (1). Moreover four 1-m^2 areas with 4 different mean crop heights, covering the full range of heights observed previously were selected for biomass measurements. Biomass samples were subsequently dried out in the oven. Crop height, wet biomass and dry biomass measurements were used to establish an empirical relationship between biomass water in corn and crop height.

2.6 Cosmic ray neutrons monitoring

In the experimental site, two "types" of cosmic-ray sensors (CRS-1000, Hydroinnova, Albuquerque, USA) were installed. These devices only recently became available commercially. One probe contained two proportional counters, one counter moderated by a low-density polyethylene surrounding and a second, bare counter without moderator (Fig. 2a). The second CRS had a moderated proportional counter only, but was identical to the first otherwise. Moderated counters monitor epithermal to fast neutrons, whereas the bare counter measures neutron more in the thermal energy range. All these neutron detectors applied at the field site are proportional counters filled with He-3 gas (2-atm pressure). Neutron detector tubes interface directly to a Neutron Pulse Module, NPM, (Q-NPM-2000-HV, Quaestra Instruments LLC, Tucson, AZ) with integrated 2000V high voltage supply and Multi-Channel Analyzer (MCA).

The sensors were mounted on a pole in the middle of the field (52.431 N, 13.021 E, WGS84, 84 m.a.s.l.) at a height of 1.50 m above ground surface in order to collect neutrons from a footprint (Fig. 1), with maximum 600-m diameter, as specified by Desilets et al. (2010). The two CRS were placed with a distance of about 6 m, thus purposely with a large overlap in their footprint (Fig. 2b). Neutron pulse counting modules of CRS were set-up to record counts every 20 min; in data processing, neutron counts were integrated in 1-h time intervals.

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2.7 Soil moisture network and field campaigns

In parallel to measurements of neutron counts, soil moisture data at point-scale was monitored by using classical techniques. A soil moisture network consisting of 16 Theta probes MR2 (Delta-T Devices Ltd., Cambridge, UK) with data loggers were installed in the experimental site. The probes measure the soil moisture based on the frequency Domain Reflectometry (FDR) approach. Sampling design in the first monitoring period considered use of 16 MR2s on the surface level spaced as shown in Fig. (1). Some of the MR2s were damaged during this period by animals or intruding water. The second monitoring period only used 5 locations in the experimental field: point 8 (center), point 9 (north), point 7 (south), point 4 (west) and point 12 (east) as shown in Fig. (1). Each location in the second period considered three different depths for MR2 probes (surface representing 5-cm depth, 20-cm depth and 40-cm depth). Values in different depths during the winter period were similar and for a consistent interpretation between summer and winter campaign we here used only the close-to-surface values.

Calibration of classical soil moisture devices was carried out collecting undisturbed soil samples during the different seasons (Table 2). Soil samples, 100-cm^3 soil cores (UGT, Muencheberg, Germany), were used for gravimetrical estimation of soil moisture and bulk density. Also, soil texture was measured by means of the hydrometer method (Beverwijk, 1967), and classified by the United Stated Department of Agriculture (USDA) classification.

2.8 Calibration of CRS

In literature, calibration technique for CRS is only done by modeling neutron transport using neutron transport simulations. Desilets and Zreda, (2008) and Desilets et al. (2010) evaluated the fitting parameters of Eq. (1) by means of simulating the relative neutron flux for a given volumetric soil moisture under simplified conditions in MCNPX. Subsequently, an equation such as Eq. (1) was adjusted to match field soil moisture values (two points in time) by translating the curve until a least-squares fit was achieved.

Our approach implemented in this study considered calibration of CRS based on continuous data from a classical soil moisture network (Sect. 2.7). Calibration data consisted in surface soil moisture values from MR2s in 16 locations inside the footprint (Fig. 1). Since penetration depth of cosmic ray method is variable depending on mean soil moisture values in the footprint (shallow penetration under only wet condition), a calibration technique of CRS using surface soil moisture preferably should use data from medium wet to wet conditions (e.g. after precipitation events), where vertical penetration depth of CRS is comparable to vertical coverage of surface MR2.

The procedure to normalize neutron counting rates observed in moderated counter (N_{raw}) for estimation of soil moisture needs a counting rate representing dry conditions. This neutron counting rate under dry conditions ($N_{\text{dry\_raw}}$) was taken from a period where the lowest soil moisture values were measured in all MR2s. However, the classical soil moisture data here are only used to indicate dry conditions not to provide a soil moisture value, and only a counting rate is used from this period.

Since Eq. (1) presents three unknown fitting parameters, we decided to use also three soil moisture time series data of surface from MR2s (ranging between mean soil moisture and maximum soil moisture values) in order to calibrate the CRS. These parameters were estimated by minimizing the root mean square error (RMSE) between MR2 and CRS data defined as follows

$$\text{RMSE} = \sqrt{\frac{\sum_{1}^{n}(\theta_{\text{CRS}} - \theta_{\text{MR2}})^2}{n_p}} \tag{6}$$

where θ_{CRS} is volumetric areal mean soil moisture inferred from CRS measurements, θ_{MR2} is the hourly value of volumetric soil moisture (mean value from 16 locations) and n_p is the number of points considered in calibration data. Subsequently, the soil moisture determined using the set of calibrated parameters was applied for the whole summer observation period and another period after harvest in winter.

The datasets used to estimate RMSE considered hourly soil moisture data. Soil moistures values from CRS in Eq. (6) were estimated by using a 6-h moving average of neutron counting rates. Either a moving average or longer integration periods of neutron data is required to achieve the desired accuracy of soil moisture estimations, because in low altitude sites (e.g. Bornim) counting rates are notably smaller than at higher altitudes, which were used in the previous study (Zreda et al., 2008; Desilets et al., 2010).

3 Results and discussion

3.1 Neutron counts under different field conditions

Different scenarios observed in Bornim showed a first opportunity to distinguish the influence of different presences of water (biomass water, soil moisture and snow pack) on the cosmic ray method. In Table 3, we summarize ranges of neutron counting rates observed for 3 types of field conditions. Though soil moisture varied in these periods, to begin with we just report measured rates. Periods when the field was cropped or bare did not show significant difference in neutron counting rates. We found that the ratio of “bare” counts to the difference of “moderated” counts and “bare” counts, is a parameter suited to distinguish different field conditions. Here, we name this ratio as field neutron ratio (N_f) and its value could be a parameter to identify different field conditions from neutron data alone. The field neutron ratio changes with the count rate level and is plotted versus the difference of “moderated” counts and “bare” counts (Fig. 4). The ratio N_f ranged between 1.21 and 2.38 for cropped-field and between 1.24 and 2.34 for a bare-field condition. Both follow well a similar power law relation. Though N_f is slightly higher for cropped than bare field, the result overall corroborated that there was not a significant difference between bare and cropped conditions.

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One important issue in the ongoing-development of the cosmic ray method is to quantify the influence of biomass. Therefore, direct measurements of plant biomass were carried out in this study. We determined an empirical relationship between wet and dry corn biomass per m^2 and mean corn height ($r^2 = 0.98$, data not show). By that, biomass water and dry biomass in the CRS footprint were evaluated by measuring crop height at a number of locations. Two field campaigns (cf. Sect. 2.5) showed that height of *Zea Mays* strongly varied, showing values between 50 and 190 cm with a mean of 143 cm (Fig. 3). These campaigns took place only a few weeks before harvest. Thus, the biomass and especially biomass water may have not increased further, or even declined, because maize tends to dry at the end of summer. Very sandy locations showed reduced crop height. In the center and east, for example, soil had a higher silt and clay content and supported better crop growth. Assuming the maximum crop height for everywhere in the footprint, biomass water was maximally 100 Mg ha^{-1} in comparison to soil moisture this constitutes only 14.95 % of the water mass for a 0.45-m soil column (mean CRS penetration) with a mean volumetric soil moisture of 15 %. This can be taken as a maximum estimate. We can infer that a maize crop, in terms of biomass and biomass water, as a cosmic ray neutron moderator, is of substantially less influence on neutron counting rates than soil moisture. This impact on neutron counting rates may be higher only for even drier conditions, e.g. $\theta < 0.05$, or higher biomass cover than our maximum maize estimate. However, these are quite unlikely conditions, even more in combination, and therefore, we hypothesize that this assumption is true for cropped field in general.

During winter there was an early and relatively long period with a snow cover, starting on 2 December 2010 with 8 cm. Evaluating a five weeks period with continuous presence of snow cover (until 9 January 2011), neutron counting rates were slightly less than observed under bare field and cropped-field conditions (Table 3). Moreover, periods with and without snow cover could be distinguished by N_f (Fig. 4). Values of N_f were clearly shifted to larger values if a snow cover was present. Values of N_f between 1.24 and 5.93 corresponded to the snow-covered period. We can conclude that snow cover plays a more substantial role on moderation of neutrons and shifting counting rates more than both biomass and soil moisture to higher N_f values (Fig. 4).

3.2 Calibration for soil moisture estimations

3.3 Classical monitoring network

Due to the relative homogenous classification of the soil type in the field (Sect. 2.4), the same calibration function for all MR2 probes could be used. A standard calibration function for mineral soil type provided with MR2 was tested against soil samples (Fig. 4). Gravimetric soil moisture was converted to volumetric soil moisture by multiplying bulk density estimated from undisturbed soil cores. The mean value of bulk density was 1.40 $\mathrm{g\,cm^{-3}}$ with a standard deviation of 0.12 $\mathrm{g\,cm^{-3}}$. Volumetric soil moisture estimated from undisturbed soil cores varied between 0.049 and 0.233 with a mean value of 0.14. The MR2 measurements gave values between 0.106 and 0.283 with a mean value of 0.16. The coefficient of correlation between MR2 data and field measurements of soil moisture was 0.84. Due to this good representation, we used the standard calibration function for mineral soil type without adaptations.

3.4 Cosmic ray sensor (CRS)

Cosmic ray neutrons observed in two different probes had a similar response. Fast neutrons monitored in two CRS showed a correlation coefficient of 0.81 for a 1-h integration period (Fig. 5a). For an integration period of 6 h, and thus a lower statistical variability of counts, the correlation between two probes increased to 0.97 (not shown). This demonstrates that the counters functioned in the same way, and also that the 6-m distance between probes did not lead to significant differences, indicating a footprint radius truly larger than this.

Neutron rates were indeed inversely correlated to local atmospheric pressure as expected (Fig. 6b). After local correction of neutrons counts due to fluctuations of atmospheric pressure (between 1000.10 and 1026.96 mbar), neutrons ranged between 781 and 1103 counts per hour. The maximum value of neutrons per hour (1067), which coincided with a period of no precipitation events and minimum soil moisture values, was used as $N_{\text{dry\_raw}}$ for normalizing neutron counts of Eq. (3).

For calibration to relate neutron count rates with soil moisture according to Eq. (1), three datasets representing soil moisture values shortly after rain events with maximum cumulative values (16.7-, 8.2- and 4.9-mm) were selected. These datasets of 26 h (between 29 August 2010 13:00 and 30 August 2010 14:00), 20 h (between 4 September 2010 17:00 and 5 September 10 12:00) and 14 h (between 13 September 2010 17:00 and 14 September 2010 06:00) had soil moisture mean values of 0.261, 0.191 and 0.141, respectively (Fig. 6a). By calibration a good fit between the soil moisture MR2 data and estimations by CRS was obtained with values of 0.465, 0.1125 and 0.49 for the fitting parameters a_0, a_1 and a_2, respectively. These fitting parameters showed a small minimum RMSE of 0.019. This value of RMSE is similar to the analytical precision of CRS for a 6-h integration period (0.013), which can be inferred from the standard deviation of mean neutron counting rate (5504 counts in 6 h). The coefficient of correlation between CRS soil moisture predictions and mean value of MR2 soil moisture observations was 0.98 (Fig. 6b).

The calibration function mathematically holds for soil moisture between full saturation and very low soil moisture ($N_R \approx 1$). The calibration period covered N_R values between 0.784 and 0.906. Only for lower N_R values (i.e. wetter conditions) the maximum soil moisture would be reached, in the case of our field site this is the case for $N_R = 0.72$ ($\theta = 0.38$). Also, for N_R lower than that the calibration curve can be applied in case the water mass stored in the soil is complemented by water stored in form of snow, (snow water equivalent), which also will moderate neutrons. However, there is a mathematical limit for applying this calibration curve and for our set of parameters $N_R >> 0.12$.

The values of fitting parameters derived for our field site did not coincide with values reported by Desilets et al. (2010). They reported values of 0.0808, 0.372 and 0.115 for the fitting parameters a_0, a_1 and a_2, respectively. These values were derived by neutron flux simulations for a generic silica soil matrix and successfully applied at a location in Lewis Springs, Arizona, USA (31.562 N 110.140 W, WGS84, 1233 m a.s.l.). Though using the same type of calibration equation, these parameter values are not directly comparable. Different field locations and different counters or counter settings would need corrections for different neutron attenuation coefficients of soil matrix and air, soil bulk density, altitude, detector sensitivity, variability inside the CRS footprint and possibly incoming cosmic ray intensity fluctuations. However, the mathematical relation between "count rates" and soil moisture indeed seems applicable, as supported by the good fit of our data, but values of fitting parameters from Eq. (1) seem not easily comparable or transferable between field sites. Instead, we take the approach to calibrate a CRS at a specific field site using independent soil moisture measurements at three short time periods and subsequently using this calibration curve for observations at other times and possibly at similar locations (e.g. at the same hillslope or small catchment). In the following we report how we tested the CRS soil moisture measurement during the full observation period in summer and also during a winter period with snow cover.

3.5 Test period during summer

Applying these fitting parameters, soil moisture values derived from hourly cosmic-ray neutron counts are shown in Fig. (8). A good agreement was observed between time series of soil moisture data by CRS and mean soil moisture from the MR2s located in the CRS footprint. Furthermore, the temporal patterns of soil moisture inferred from MR2s and CRS are similar, despite their different measurement volumes. Mainly, CRS soil moisture pattern was inside a range of one standard deviation of MR2s, except in two periods: (i) between 02 September 2011 00:00 and 2 September 2011 14:00 and (ii) between 9 September 2011 11:30 and 11 September 2011 11:30.Values in this first period fall into a range of two standard deviations of MR2 average mean values. However, during the second period there was a clear overestimation of soil moisture by the CRS method compared to MR2 values, longer and more than to be expected by statistical deviations. The reason for this probably is not a deviation of the MR2, but from the CRS. At present we can only speculate about reasons, such as temporal failure of pressure correction, reduced voltage supply of the counter or reduced solar activity. After this period came down to meet the MR2 values and responded properly to precipitation events.

Overall, the RMSE between hourly soil moisture values by CRS and spatial mean hourly values of soil moisture from MR2s was 0.039 for the complete cropped field period. This RMSE is similar to the analytical precision of CRS (0.033) expected from a mean counting rate of 918 neutrons per hour.

Furthermore, the cosmic ray method responded well and quickly to precipitation events, as neutron counting rates decreased during precipitation events and stayed lower afterwards; thus CRS-derived soil moisture values increased for those periods as they should (e.g. after events 29 August 2010 and 4 September 2010). However, when CRS data were smoothed with a 6-h moving average, due to the statistical variability of neutron counting rates, steep increase of soil moisture may not be reflected perfectly. For example, the cosmic ray method resulted in an increase of soil moisture a few hours (~6–7 h) before precipitation actually occurred (e.g. events 8 September 2010 06:00 with 0.9 mm and 12 September 2010 23:00 with 0.3 mm).

3.6 Test period during winter with periods of snow cover

After harvest of corn, the CRSs were operated at the field site again by end of November 2010. The CRS data retrieved were used for assessing the difference to crop field of summer and to test for the impact of snow cover (Fig. 9). This winter had an early cold period with snow fall. Classical soil moisture sensors, MR2 probes, could not provide reliable measurement of soil moisture during parts of the winter period probably due to freezing conditions. Air temperature data was registered by the CRS directly. We observed that when air temperature fall below 0 °C, electrical output of MR2s sharply decreased, and then for negative air temperatures stayed below the usual range of 200 to 850 mV, observed under crop and bare conditions. Overall, we found quite good correlation between air temperature and functionality of MR2 probes (not shown) in order to identify periods where MR2s data could be used. Thus, these periods when MR2 probes were out of range are marked with an arrow between vertical dashed lines in Fig. 9. In the intermediate periods of varying length the MR2 data seem to reflect realistic soil moisture conditions, except a period of one week beginning of March showing strong fluctuations.

In this winter period the CRS calibration via Eq. (1) with soil moisture data from cropped-field conditions was applied without modifications. Therefore, the CRS derived data could be tested for periods of bare field conditions with and without snow cover. During periods of bare soil without snow cover, soil moisture by CRS reproduced well the values observed in the field (Fig. 9), as long as the MR2s were able to provide correct data, e.g. mid and end of March. In cold periods without snow cover the CRS method gave plausible values, opposed to the MR2, e.g. for the period end of January to the first days of February. It also showed an increase in response to precipitation (not resulting in snow cover). Moreover, CRS measurements of soil moisture were unaffected by sharp drops of air temperature, thus soil temperature.

Since the MR2s were not properly working under low temperatures, estimations of CRS were also validated with results from a fifth soil sampling campaign (Table 2). In this campaign, mean soil moisture was 0.238 with a standard deviation of 0.014. This is comparable to the areal mean soil moisture of 0.22 estimated by means of cosmic ray neutron method (averaged during the time interval required for the sampling campaign).

In period when bare soil was covered with snow, neutron counting rates were significantly lower, thus Eq. (1) predicted higher values of θ. Such soil moisture values inferred by CRS have to be seen as a measurement of the water mass stored in and on the soil in the footprint of the CRS. Nominal soil moisture values derived for these periods exceed porosity values of loamy sand (38 %) in the field. This over-estimation of soil moisture reflects the additional moderation of hydrogen mass in snow, as has to be expected, and requests a different interpretation of these nominal soil moisture values.

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Normalized neutron counting rates and snow cover data, both as a daily average, suggest that these two could well be related with the calibration curve based on Eq. (1) as shown in Fig. 10. Lower values of N_R were measured in higher snow cover. Maximum and minimum daily snow covers of 41 cm and 8 cm corresponded to N_R values of 0.47 and 0.80 (daily integration), respectively.

The presence of snow modifies the energies of the neutrons detected, as can be seen clearly in Fig. 4. However, we have not applied a procedure to distinguish between snow moderated and non-snow moderated neutrons, though this could be aimed for in principle. Instead, we take this shift as indication of the impact of snow and otherwise limit our interpretation to a nominal soil moisture indicating the combination of real soil moisture (possibly frozen) and snow water mass equivalent, as discussed above.

When snow started to melt neutron counting rates increased resulting in a steep drop of (nominal) soil moisture until 10 January 2011, when there was no more snow cover on the field. The N_R values were higher again 0.72 and therefore measurements by CRS corresponded again to soil moisture measurements by MR2.

4 Summary and conclusions

The work presented has tested the novel cosmic ray sensing method, especially in a new geographical context that may allow for the application of the method in investigations of local soil water balance and catchment hydrology. Furthermore, an application procedure was explored that now could be adopted by others relatively easily for measuring integral soil moisture at intermediate spatial scales.

Our results show, that the CRS method can be successfully applied also for agricultural fields, even at low altitudes where neutron count rates are lower. This inherent disadvantage of lowland applications limits the temporal resolution and imply that an integration period of several hours, or an equivalent smoothing window, are needed to obtain results without too much statistical variability. Then results after an initial calibration step compared well with soil moisture measured in a monitoring network by

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FDR sensors and soil sampling, both representing a shallow depth of about 5 cm. In difference, the cosmic ray sensing method accounts for contributions of soil moisture also from deeper depth. In our calibration approach, fitting parameters needed to infer soil moisture from the neutron counting rates were calculated by taking three periods of medium soil moisture data, some time after precipitation events allowing for a redistribution of soil moisture from surface to depth, thus also not exhibiting a strong surface drying. The results also indicated that the integration area of the CRS is up to several hundred meters, as given by Zreda et al. (2008). Nevertheless, both in horizontal and vertical direction it is an open question how the CRS values reflect the real soil moisture distribution at a particular field site and how the extension and the shape of its integration footprint are.

Another aspect is the influence of hydrogen stored in other forms besides soil moisture such as water in soil materials or plant roots, carbohydrates, above-ground biomass water or snow. As our results suggest, there may be an influence of bound water and carbohydrates which may impact the values of fitting parameters, however these will not cause a systematic deviation of calibrated soil moisture values. Also, above-ground crop biomass seems not to lead significant changes in CRS-derived soil moisture values and therefore, this may not need to be accounted for in CRS applications explicitly. However, other vegetation cover, for example trees, probably will have more substantial impact on neutron count rates and subsequently soil moisture values. Snow cover of the soil has a major influence on neutron count rates, shifting the nominal soil moisture values easily to more than double or even triple the real soil moisture values. Since there is good inverse relation with snow height and additionally a shift towards relatively more counts in the bare than the moderated CRS counter, it could be possible to subtract the snow water mass contribution or even use it to estimate snow height. Moreover, the CRS was giving reliable values of soil moisture also for periods of freezing conditions without snow cover, opposed to the measurements with MR2 failing in these periods.

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Our CRS operational procedure used for application of integral soil moisture measurements on farmland via sensing of cosmic-ray neutrons in summary was (i) selection of field site location with a 100–300 m radius with relatively homogeneous soil, vegetation, and relief; (ii) installation of a (commercially available) CRS probe on a pole with a height of around 1.5 m, best with a moderated and a bare counter, data logger, solar panel, air humidity and temperature measurement and possibly remote data transfer; (iii) monitoring site specific soil-moisture data in periods of a few days covering at least one dry period and two periods varying between medium wet to wet conditions; use these data for calibration of the cosmic ray probe on the basis of Eq. (1) by adapting the three fitting parameters after correcting neutron count rates for air pressure variations; (iv) derivation of integral soil moisture values on hourly basis, with possible subsequent accumulation or smoothing; and (v) observation of snow cover or at least check the relative difference of counts in moderate and bare CRS counter for N_f values shifted to values outside the bare-field values; possibly use a relation as shown in Fig. 10 to correct count rates for influence of snow cover, if distinguishing between snow and soil water is desired.

Times series data of precipitation in comparison with CRS soil moisture values show overall an excellent response of the cosmic ray method to these hydrological events, also smaller ones. The CRS-derived soil moisture values are consistent with other measurements in the first 10 cm of topsoil, but shall also reflect water somewhat deeper than that. For shorter periods there may be a systematic deviation of the CRS values, as observed once in this study for a duration of three days with a shift of about 5 % soil moisture. The occurrence and reasons may be related to changes in incoming primary cosmic ray intensity fluctuations, local air pressure differences or heavy cloud cover which will have to be investigated further. Overall, our investigation suggests that the cosmic ray sensing method with the type of neutron counters used here can very well be applied in a lowland agricultural field, and likely in a majority of European sites. Nevertheless, methodological improvements will be required. In general, the CRS method has the potential to become a worthwhile and not too expensive extension

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of soil hydrological measurement methods. It lends itself to extended monitoring as well as shorter-period observations due to the relatively simply installation and mobility. This data should be a valuable input for the observation of hydrological water balances and especially the modeling of small to medium catchments.

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Table 1. Nuclear properties of major rock constituents: Atomic number (Z), atomic weight (A) in grams, total scattering cross section (σ_S), absorption cross section (σ_a) for 2200 $\mathrm{m\,s^{-1}}$ neutrons (20 °C), and average number of collisions (NC) required to reduce a neutron's energy from 2 MeV to 0.025 eV by elastic scattering. Cross sections units in barn (1 barn = 10^{-24} $\mathrm{cm^2}$) and values were extracted from Sears (1992). Calculation of number of collisions is based on Eq. (12.8) p. 845 in Krane (1988).

Element	Z	A	σ_S	σ_a	NC
H	1	1.00794	82.02	0.3326	26
B	5	10.811	5.24	767	108
C	6	12.0107	5.551	0.0035	119
N	7	14.0067	11.51	1.9	137
O	8	15.9994	4.232	0.00019	155
Na	11	22.98987	3.28	0.53	219
Mg	12	24.305	3.71	0.063	230
Al	13	26.98154	1.503	0.231	255
Si	14	28.0855	2.167	0.171	265
Cl	17	35.453	16.8	33.5	332
K	19	39.0983	1.96	2.1	365
Ca	20	40.078	2.83	0.43	374
Mn	25	54.938	2.15	13.3	509
Fe	26	55.845	11.62	2.56	517
Ag	47	107.8682	4.99	63.3	991

Table 2. Description of soil sampling campaigns at experimental site.

Campaign	Date [dd/mm/yyyy]	Season	No. of Samples	Mean soil moisture [–]	Standard deviation [–]
1	03/08/2010	Summer	18	0.169	0.028
2	11/08/2010	Summer	18	0.066	0.015
3	16/08/2010	Summer	19	0.198	0.029
4	06/09/2010	Summer	19	0.132	0.052
5	11/02/2011	Winter	5	0.238	0.014

Table 3. Range of neutron counting rates observed in different field conditions.

Condition	Period of observation (with short gaps due to battery failure)	Moderated counter (neutrons per hour)	Bare counter (neutrons per hour)
Cropped soil	27-08-10 until 14-09-10	790-1067	500-659
Bare soil (without snow)	26-11-10 until 01-12-10	802-1045	489-650
	10-01-11 until 25-03-11	687-1060	398-649
Bare soil + snow cover	02-12-10 until 09-01-11	521-930	387-621

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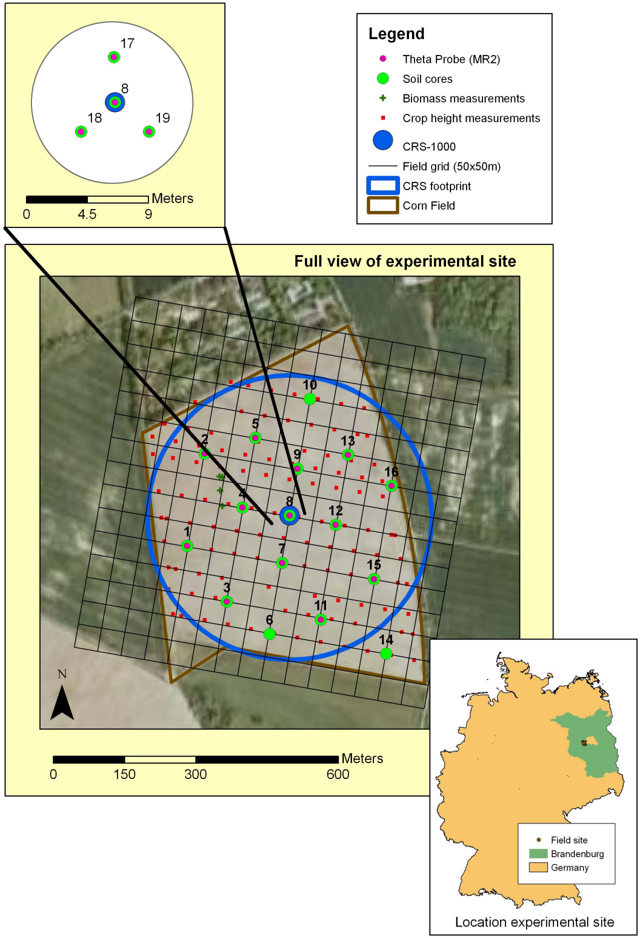

Fig. 1. Location of experimental site and its hydrological instrumentation.

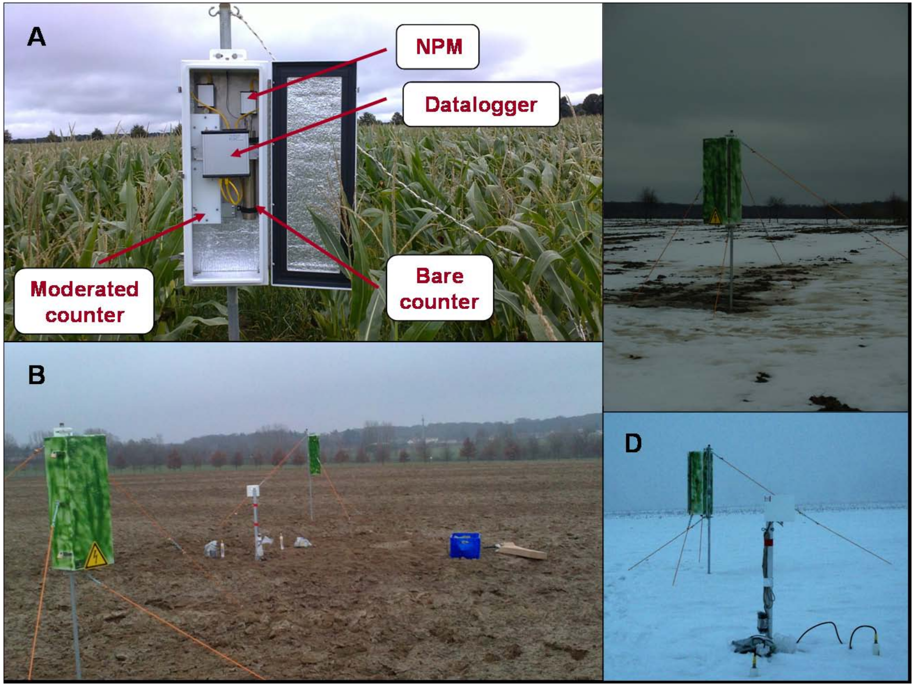

Fig. 2. Cosmic ray sensors (CRS) under different field condition in Bornim: **(a)** Two-counters CRS and its parts in cropped corn field, **(b)** picture of two CRS in bare field condition, **(c)** picture of CRS at the beginning of snow cover condition, and **(d)** picture of CRS, rain gauge and Theta Probes (MR2) during a day with maximum snow cover.

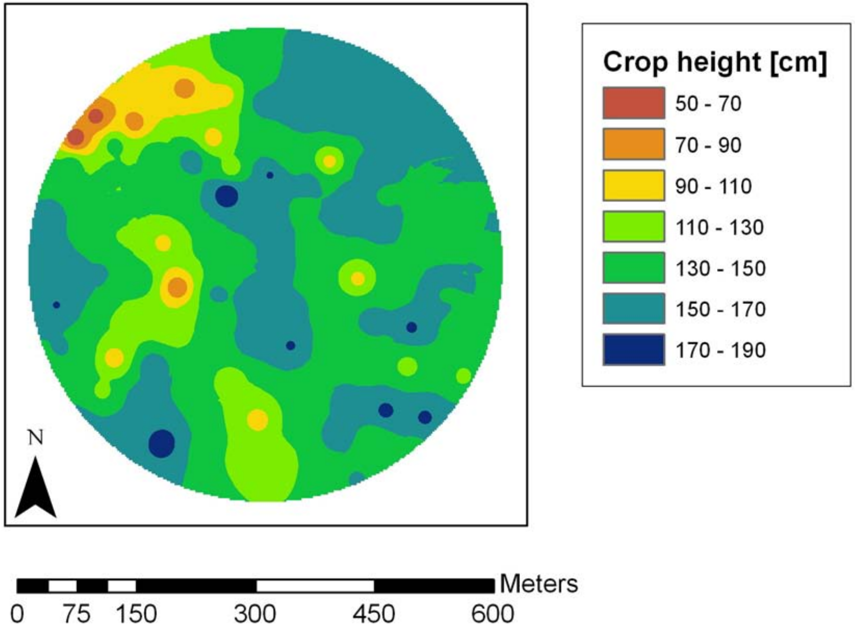

Fig. 3. Spatial variability of corn crop height in CRS footprint as observed on 19 August 2010.

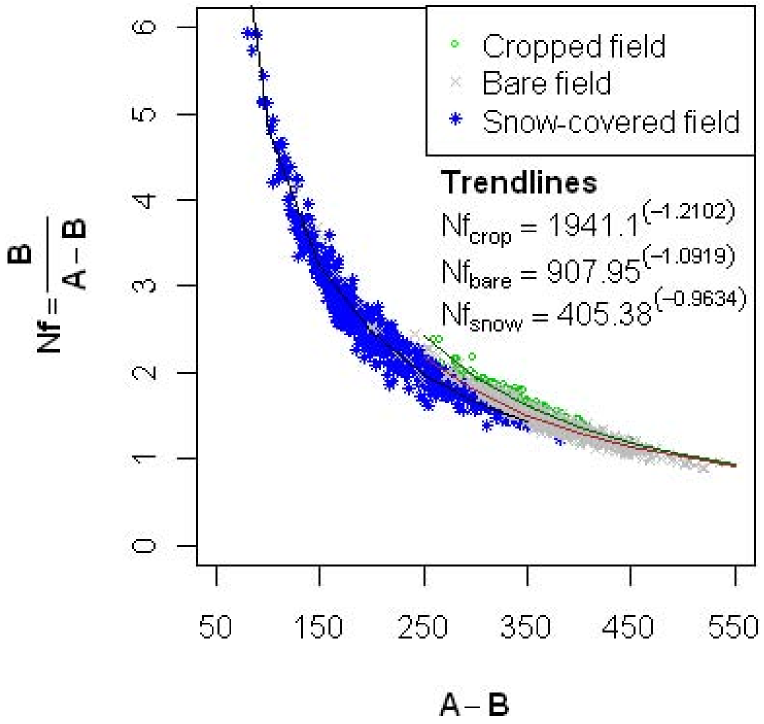

Fig. 4. Neutron counts in different field conditions. In the vertical axis, *Nf* is the field neutron ratio defines as ratio of bare counts per hour **(B)** over difference of moderated counts per hour **(A)** and bare counts per hour **(B)**. In the horizontal axis, difference of moderated counts minus bare counts per hour.

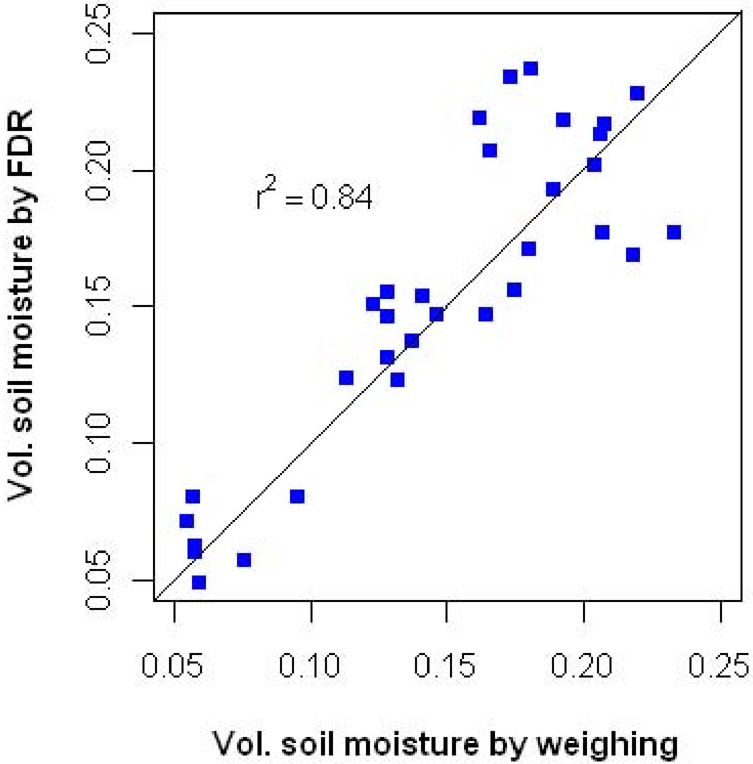

Fig. 5. Calibration of Theta Probes (MR2): observed soil moisture from soil cores and soil moisture measured by MR2s.

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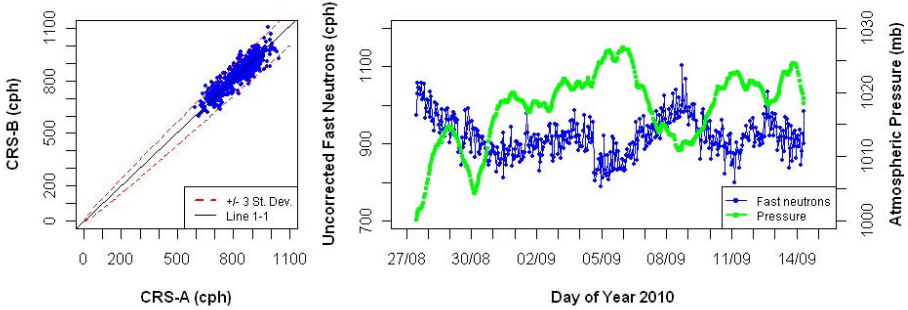

Fig. 6. Fast neutron counting rates under cropped field conditions: (Left) Correlation of fast neutron counting rates per hour between two cosmic ray probes, and (right) Temporal variability of uncorrected fast neutron counting rates per hour and local atmospheric pressure.

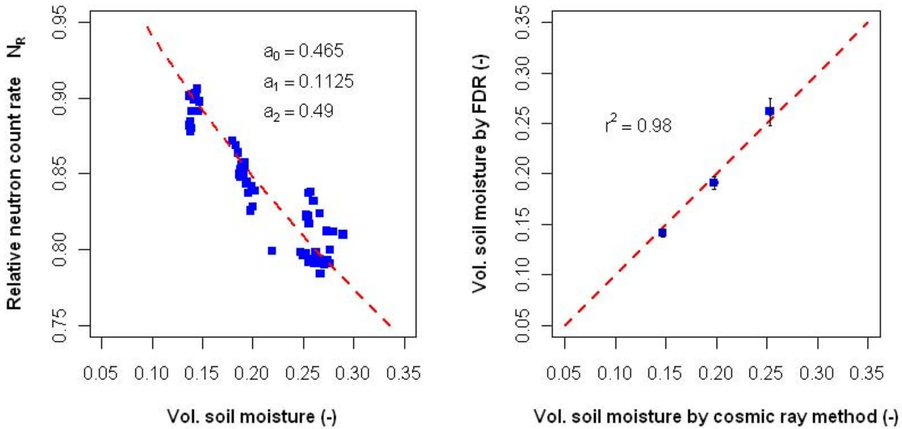

Fig. 7. Calibration of the cosmic ray method: (Left) Calibrated function of soil moisture estimation by cosmic ray neutrons (Eq. 1) and (Right) correlation between soil moisture measured by CRS and measured by MR2 probes.

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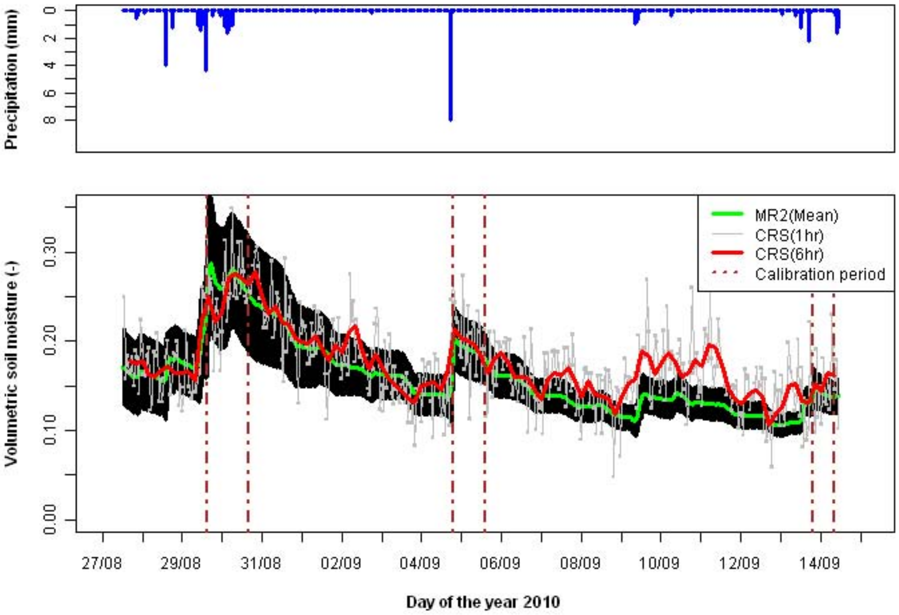

Fig. 8. Volumetric water content as volumetric soil moisture inferred by cosmic ray method plotted for a period of cropped field condition. Upper graph: hourly precipitation time series data measured in ATB weather station. Lower graph: soil moisture time series data measured by MR2 probes (spatial mean hourly value in green and one standard deviation in black band) and CRS (1-h estimations and 6-h moving average in gray and red colors, respectively). The three periods used for calibration of CRS are shown between vertical dashed lines.

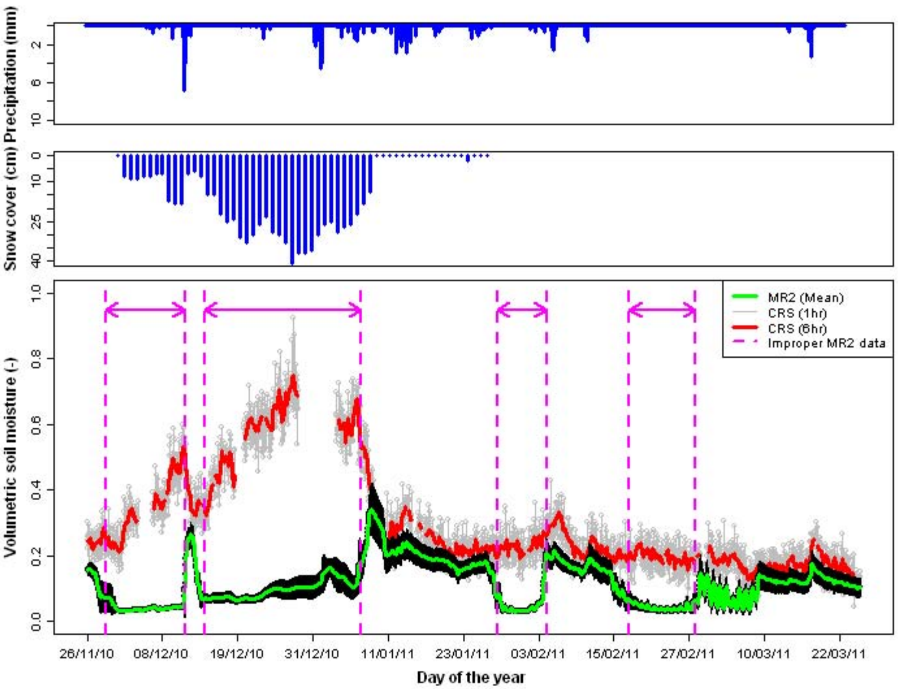

Fig. 9. Volumetric water content measurement by cosmic ray method during the winter period. Two upper graphs: hourly precipitation (mm) in ATB weather station and daily snow cover in PIK weather station. Lower graph: soil moisture time series data measured by MR2 probes (spatial mean hourly value in green and its standard deviation in black band) and CRS estimations (1-h estimations and 6-h moving average in gray and red colors, respectively). Periods where MR2 did not work properly due to low soil temperature conditions, are shown between vertical dashed lines.

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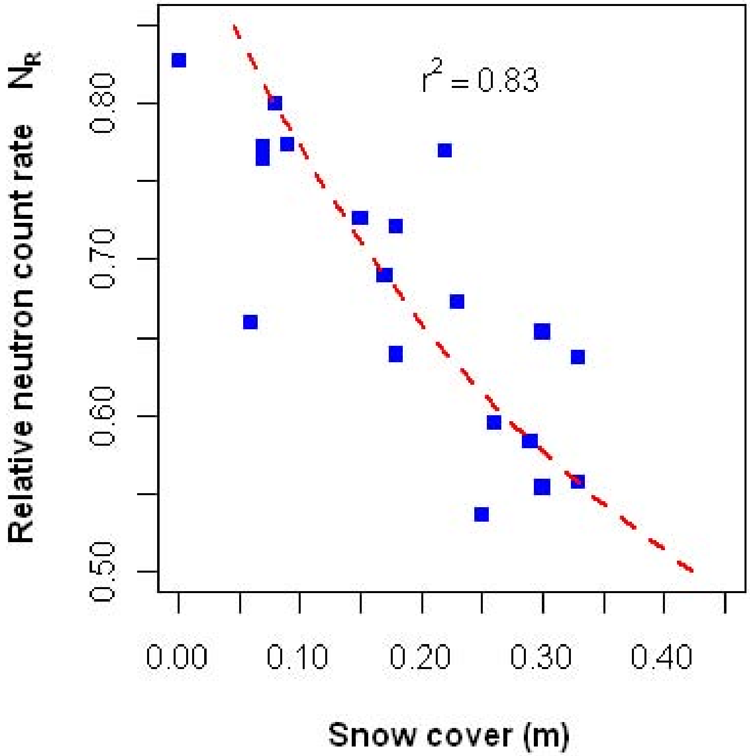

Fig. 10. Normalized daily neutron counting rate (N_R) versus daily snow cover in PIK weather station.