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Application of cosmic-ray neutron sensing to monitor soil water content in an alpine meadow ecosystem on the northern Tibetan Plateau

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SUMMARY

Cosmic-ray neutron sensing (CRNS) is a new method for continuously monitoring mean soil water content (SWC) on a hectometer scale. To evaluate the application and accuracy of the method for SWC observation in an alpine meadow ecosystem (AME), we installed the CRNS in a flat meadow near the Naqu prefecture on the northern Tibetan Plateau. We collecting soil samples and applying the system by the oven-drying method. A weather station was also installed near the CRNS for monitoring basic meteorological variables and the soil temperature and water content at various depths. Three Em-50 instruments for monitoring SWC and soil temperature were buried in three sub-quadrats northwest, northeast and southeast of the CRNS at distances of 460, 370 and 373 m, respectively, to observe the variation of SWC at the various depths. The footprint of the CRNS for SWC observation in the meadow was about 580 m, and the mean measuring depth was about 31 cm according to the general calculation equations. The reference neutron flux for dry soil (N_0) had a mean and coefficient of variation of 8686 and 3%, respectively, and remained substantially invariant throughout the measuring period. The five SWCs from the independent field samples almost passed through the SWC trend of the CRNS, the root mean square error (RMSE) was 0.011 $m^3 m^{-3}$ for the CRNS and oven-drying method. The time series of SWC measured by the CRNS agreed well with the mean SWC series to a depth of 20 cm measured by the weather station. The trend of SWC measured by the Em-50s generally agreed with the trend of SWC measured by the CRNS, but some values and variations of SWC differed between the Em-50s and CRNS data. Because of the good agreement between the CRNS and independent field samples, we suspect that this disagreement is due to an insufficient representativeness of point observations and the distances of the points from the CRNS. The diurnal variation of hourly SWC from the CRNS was sinusoidal during a dry period, peaking at 11:00 and was minimum at 18:00 (Beijing time), with a range of 1%. Overall, the CRNS measured SWC in the AME with an acceptable accuracy, providing a scientific basis for the promotion and application of the CRNS in high, cold ecosystems.

1. Introduction

Soil moisture is an important component of Earth's water and sustains the existence and multiplication of surface life and the stable development of land-surface ecological systems. Soil moisture controls regional hydrometeorology by assigning rainfall into infiltration and runoff and controls the exchange of energy between the land surface and the atmosphere by evaporation (Jia and Shao, 2013). Accurate observation of soil water content (SWC) could improve the accuracy of weather and climate forecasting, prevent a variety of weather-related disasters and improve the management efficiency of agricultural water (Rosolem et al., 2014).

SWC can be monitored by many methods, such as oven drying, neutron probes, time domain reflectometry and frequency domain reflectometry (Vereecken et al., 2014). All these are point measuring methods, the measuring scale is small and the

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representativeness is insufficient in space. Remote sensing methods, however, can invert SWC at large scales at shallow inversion depths and would be influenced by topography and vegetation. Cosmic-ray neutron sensing (CRNS) is a newly developed method for measuring SWC that is being rapidly adopted due to its unique advantages of automatic and nondestructive observation. Cosmic-rays are common and enter the atmosphere after penetrating Earth's magnetic field. Primary cosmic-rays interact with atmospheric nuclei and produce fast neutrons. The fast neutrons can then enter the soil and be moderated by hydrogen atoms, the main source of which is soil water, and the moderated neutrons can then be counted by the cosmic-ray probe located near ground level (Zreda et al., 2012). Hydrogen atoms are severalfold more efficient than the next most efficient element, carbon, at moderating fast neutrons. The intensity of neutrons is inversely proportional to SWC, which is the major operating principle of the CRNS. Unlike the conventional methods of measuring SWC, the CRNS can continuously measure the mean SWC of what can be conceived to be a flat-topped cylinder of soil. The radius of the horizontal footprint of the CRNS, the region containing 86% of the detected neutrons, is estimated to be about 300 m by Desilets and Zreda (2013) and from 130 to 240 m by Köhli et al. (2015) at sea level (atmospheric pressure of 1013 hPa). The surveying depth is estimated to be about 12 cm (saturated soil) to 76 cm (dry soil) by Zreda et al. (2008) and from 15 to 83 cm by Köhli et al. (2015). A hectometer scale can compensate the deficiency of soil moisture observation between point and remote sensing images.

The CRNS has been widely studied in recent years. Several methods are available to estimate SWC from the measured neutron intensity. The N_0-method (Desilets et al., 2010), the hydrogen molar fraction method (Franz et al., 2013) and the COSMIC operator method (Shuttleworth et al., 2013) were calibrated by the Monte Carlo Neutron-Particle eXtended (MCNPX) radiation transport code. Baatz et al. (2014) compared the three methods and found that they all performed similarly well during validation. The N_0 method is the simplest for estimating SWC because it requires only one parameter. Desilets et al. (2010) obtained the generalized SWC calibration equation by fitting the neutron flux obtained from the MCNPX radiation transport code and reported the values of the parameters in the equation. Franz et al. (2012) derived an equation for calculating the depth of SWC measurements. Desilets and Zreda (2013) used diffusion theory and the neutron-transport model to derive an equation for estimating the footprint radius and analyzed the factors influencing the radius. Zreda et al. (2012) systematically explained the principle, calculations, influencing factors, calibration and application of the CRNS to provide a better understanding for the wider application of this new approach. The correction of influencing factors has also received much attention. The analysis and correction of the influences of atmospheric pressure, water vapor, solar activity and aboveground biomass on the neutrons have been studied (Desilets and Zreda, 2001; Moraal et al., 2005; Rosolem et al., 2013; Coopersmith et al., 2014; McJannet et al., 2014; Baatz et al., 2015) and can improve the accuracy of the CRNS. These studies have built the foundation for the application of the CRNS method (Rivera villarreyes et al., 2011; Bogena et al., 2013; Han et al., 2014; Wang et al., 2015).

The CRNS has a solid theoretical and growing empirical foundation (Zreda et al., 2012) and has been applied in a variety of ecosystems, such as forest (Lv et al., 2014), farmland (Zhu et al., 2015) and grassland (Zhao et al., 2015), under different climatic conditions. CRNS networks have been installed in the USA (Zreda et al., 2012), Australia (Hawdon et al., 2014), Germany (Baatz et al., 2014), Africa and England (Rosolem et al., 2014). The performance of the CRNS, however, remains uncertain for degraded ecosystems with extreme climatic conditions due to the impact of vegetation, soil properties and altitude. The purpose of this study was thus to evaluate the accuracy and application of the CRNS in an alpine meadow ecosystem (AME) of the northern Tibetan Plateau and to provide a reference and scientific basis for its application in other AMEs.

2. Materials and methods

2.1. Site description

This experiment was carried out at the Station of Grassland Ecosystem Research on the Northern Tibetan Plateau of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (31.64°N, 92.01°E), on the northern Tibetan Plateau, 19 km northwest of Naqu Prefecture (Fig. 1). The average elevation is ca. 4600 m above sea level, but the relative elevation is less than 10 m in the study plot. The study area has a sub-frigid and semi-humid monsoon climate with a cold and long winter. The growing season is from June to August, and the soil is frozen for the rest of the year. The mean temperature in 2014 was 0.6 °C, with a minimum of −18.8 °C on 18 December and a maximum of 13.2 °C on 25 June. The total precipitation was 592.1 mm, with 510.4 mm (86.2%) falling from June to September. Mild hailstorms occurred occasionally in the early and late stages of the 2015 growing season, but the hailstones melted immediately after the sun appeared. The mean relative humidity was only 48%. The mean atmospheric pressure is 587 hPa, which is only 58% of the pressure at sea level. The climate in the study area is generally cold, dry and windy. The soil is an alpine meadow soil, a sandy loam, with a high sand content (Table 1), indicating a small amount of lattice water. Stones are distributed sporadically in the top 30 cm of soil and extensively below 30 cm, which impedes the sampling. The zonal vegetation is alpine meadow dominated by *Kobresia pygmaea* associated with *Potentilla* spp., *Leontopodium pusillum* and *Carex moorcroftii*, all of which are annual herbs. The mean total above ground biomass was low and estimated to be 78, 51 and 93 g m^{-2} on 9 July, 27 July and 24 August, respectively.

An irregular polygonal fence was built on a relatively flat meadow beside the research station in 2011 to prevent cattle grazing and to act as the boundary of the sample plot, which was ca. 480 m wide from the southwest to the northeast and ca. 700 m long from the southeast to northwest, for a total area of ca. 33.6 ha. Sub-quadrats of 20 × 20 m were established in the northwest, northeast and southeast edges of the plot in 2011, 2012 and 2013, respectively (Fig. 1), for observing the impacts of different durations of grazing prohibition on the SWC and soil temperature in various layers. The distances from the 2011, 2012 and 2013 sub-quadrats to the center of the sample plot were 467, 370 and 373 m, respectively.

2.2. Instrumentation and measurement

2.2.1. The cosmic-ray soil moisture observing system

The cosmic-ray soil moisture observing system was installed in the middle of the sample plot (Fig. 1). Its main component is a moderated fast-neutron probe, which was filled with He-3 instead of conventional boron trifluoride, and was produced by Probe Science and Technology Ltd., Beijing, China. The probe was fixed 50 cm above the ground on a steel tube by iron wire. The system also included a data-acquisition system and a solar panel. The data acquisition system consisted of a data logger, a battery and a solar-charge controller. The battery provided the power to the system and maintained a relatively constant voltage of 12 V. A temperature sensor was installed on the solar-charge controller to measure the air temperature in the box. The cosmic-ray soil moisture