Large Area Soil Moisture Measurement Using Cosmic Rays Neutrons: The Australian CosmOz Network

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ABSTRACT

Field measurement of soil moisture is undertaken traditionally using point based measurement techniques such as neutron probes or time domain reflectrometry (TDR). Recently, a new technique has been developed that can be used to derive soil moisture at larger spatial scales by measuring neutrons that are generated by cosmic rays within the air and soil, and emitted back into the atmosphere. A study by Hendrick and Edge (1966) in the mid 1960s showed that the intensity of the fast neutrons above the ground varied with soil moisture content. The intensity of the neutron is mainly moderated by hydrogen ions located in the water and soil, and the density is inversely correlated with soil moisture. To soil scientists and hydrologists, this has opened up the possibility of measuring surface soil moisture automatically over an area of ~40 ha to a depth of ~0.5 m. The technique has the potential to fill the gap between point scale measurements (neutron probe or TDR) and soil moisture estimated using earth observation techniques (remote sensing). In Australia, 11 probes have been deployed across a range of agro-ecological zones to demonstrate the potential for larger scale soil moisture monitoring.

Key words: *soil water, cosmic rays neutrons, cosmOz, neutrons.*

INTRODUCTION

Ground-based soil moisture (θ_S) measurements have been used in a wide variety of applications including agriculture, hydrology, meteorology and in the calibration of satellites that can sense surface moisture remotely. Although highly valuable, most ground-based measurements of θ_S are made at a "point" (<1 dm^2) scale. The methods used vary from core samples (gravimetric or volumetric), TDR or capacitance probes or neutron probes. These measurements are at the point scale and it is therefore often difficult to obtain a sufficient number of θ_S values to capture the heterogeneity present in many landscapes. Quantifying the spatial variability in θ_S presents significant challenges and may preclude meaningful determination of temporal changes in soil water content.

Recently, Zreda *et al*. (2008) developed a technique to derive soil moisture estimates by measuring neutrons produced by cosmic rays. The method is based on the early observation by Hendrick and Edge (1966) showing the intensity of fast neutrons (energy 10 eV – 1000 eV) above the land surface was related inversely to the soil water content. Hydrologists and soil scientists have rediscovered this finding with the development of the cosmic rays technique. It opens up the possibility of measuring surface soil moisture automatically over an area of ~40 ha (Zreda *et al*., 2012). In summary, the sensor works by counting "fast" neutrons that are generated by cosmic rays as they pass through the Earth's atmosphere. At the land surface these neutrons are moderated by water molecules, and their count rate is predominantly a function of the water content of the soil.

METHOD

Details of the cosmic ray probe are given by Zreda *et al*. (2008, 2012) and Desilets, Zreda and Ferré, (2010). The theory behind the technique for measuring average soil moisture is given in Zreda *et al.* (2012). By placing the neutron detector above the ground surface, average soil water measurements can be made over horizontal footprint of hectares (ha), and to a soil depth of decimetres (dm). Figure 1a shows the typical installation of the sensor in Australia where the sensor is mounted above the soil surface. The mean free path of the fast neutrons is around 100 m, and therefore the sensor can detect neutrons from several hundred m away (Zreda *et al.*, 2008; Desilets, Zreda and Ferré, 2010). The depth to which the sensor can detect θ_S is dependent on the soil water content and is ~10 cm in wet soil and up to ~50 cm in dry soil (Franz *et al*., 2012a).

In 2010, CSIRO was the first organization in Australia to order 11 commercially available custom-designed cosmic ray soil moisture probes (CRS-1000, Hydroinnova, Albuquerque, NM, US). Together with university collaborators, these 11 sensors were deployed to form the CosmOz network (http://cosmos.hwr.arizona.edu /Probes/australia.php). It serves as a prototype Australian network of CRS-1000 probes designed to support sensor evaluation, research and the development of new sensor applications. The current network of 11 probes is deployed across the country in a range of soil types, vegetation cover and climates (Figure 1b).

RESULTS AND DISCUSSION

Experience to date has shown that the CRS-1000 probe needs to be calibrated for the local soil type to obtain accurate absolute (volume percent) values of θ_S. As the probe measures θ_S over such a large area, this is done by taking a large number (72) of gravimetric soil samples at distances up to 200 m from the probe (Franz *et al*., 2013). Once this calibration has been carried out, daily θ_S changes can be detected with an accuracy of ~0.02 percent. An example of the soil

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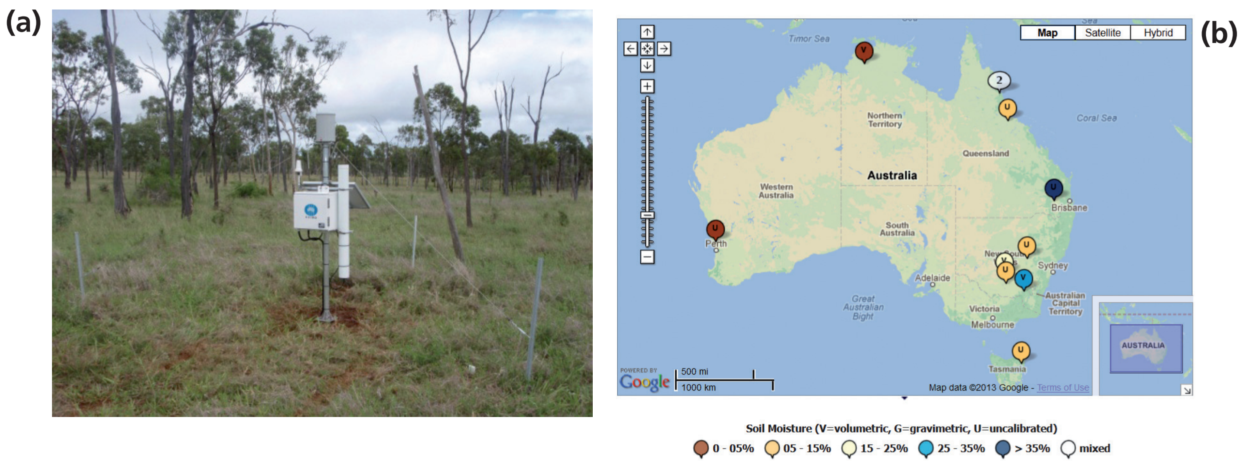

FIGURE 1. (a) A CRS-1 000 sensor installation on a grazed savannah hillslope in the dry tropics (Weany Creek, north Queensland). Picture (b) shows the locations of the current CosmOz network sites across Australia (http://cosmos.hwr.arizona.edu/Probes/australia.php).

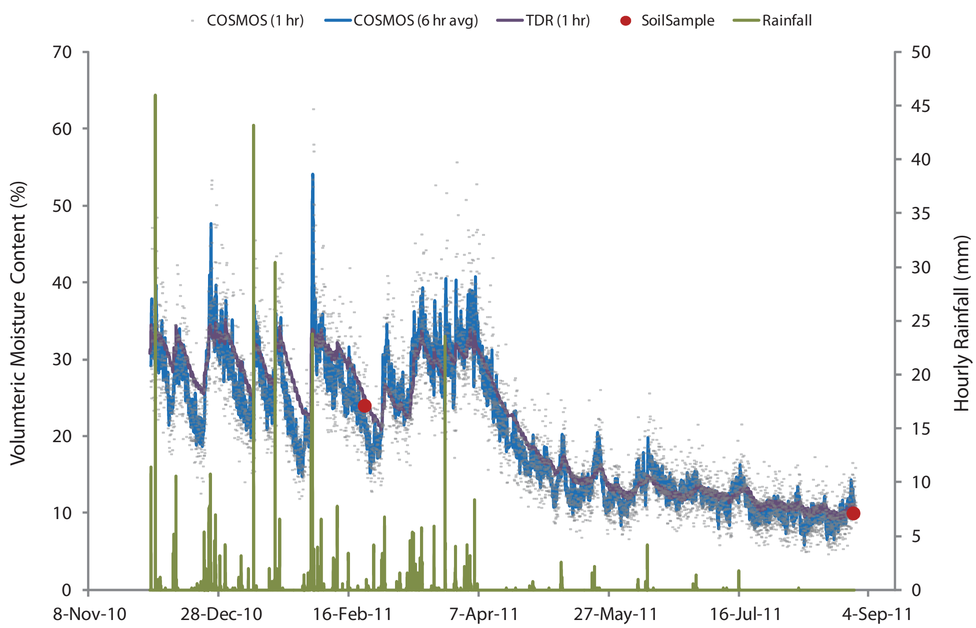

Figure 2. An example of the time series of θ_S (blue) recorded by the CosmOz probe at Weany Creek (northern Queensland). Also shown is the value of θ_S recorded using TDR probes (purple line) and rainfall (green). Two gravimetric sampling points (red) are also shown.

moisture data recorded by the CRS-1000 probe at a dry tropical site is shown in Figure 2. Over the wet season (December to April) frequent rain events raise the soil moisture content to near saturation (~40 percent) and these wetting events are followed by a period of soil drying (Figure 2). From April onwards there is little further rain and the CRS-1000 probe shows how the site dries progressively over the following months, dropping to ~10 percent by September. Figure 2 also shows the surface (0–30 cm) moisture content recorded by three conventional time-domain reflectometry (TDR) soil moisture probes. Although this is the average of only three point measurements, there is strong temporal coincidence between the TDR and CRS-1 000 time series. The CRS-1 000 soil moisture estimation equation was calibrated to the gravimetric calibration measurements made in February 2011 (Figure 2), but the second gravimetric sample in September provides an independent check of the CRS-1000 estimates.

There is significantly more variation in the soil moisture measured with the CRS-1000 probe as evidenced by the scatter in points and variation in the blue line. Less variation in water content is visible in the TDR data, because it is measuring over different depths in the soil. This is more obvious at the irrigated site (Figure 3), where there is a sharp increase in soil moisture in the surface 0.05 m shown in the TDR trace. This amplitude of the increase in θ_S is dampened in the CRS-1000 trace, showing that it is measuring the average water content over a different depth (volume) of soil, shown by the higher water content being measured with the TDR traces. These results are consistent with those reported in the literature (Franz *et al.*, 2012b).

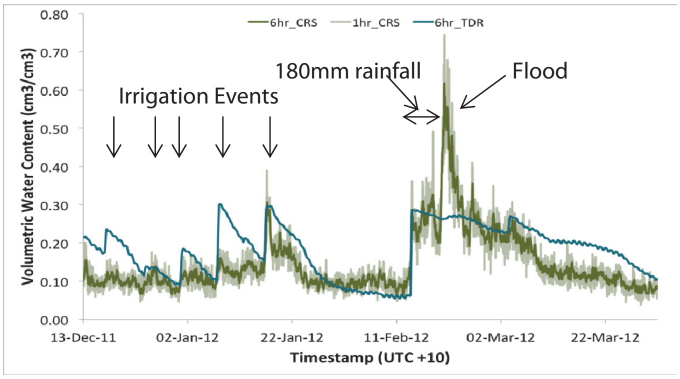

FIGURE 3. Time series of θ_S (green line) recorded by the CosmOz probe from an irrigated soil at Griffith. Also shown is the θs recorded using TDR probes (blue line).

The cosmic ray method for determining soil moisture content has some limitations. One limitation is the detection of hydrogen (H) atoms in other forms beside the soil water. For example, H can be found in the plants growing on the soil, in gypsiferous soils associated with the hydration of the calcium sulphate ($CaSO_4 2H_2O$) and the clay minerals that make up the soil (Schulze, 2002). Similarly, surface and/or flood water is measured as evidenced by the large increase in volumetric water content following 180 mm of rain at Griffith (Figure 3). If the hydrogen content is constant, as would be the case for clay minerals, its effect can be accounted for in the calibration and therefore largely becomes irrelevant. As with the neutron probe, if the calibration is done on pore and lattice water, the effect of the lattice water is handled in the calibration of the probe. However, the presence of lattice water must reduce the depth of measurement, and the effect will be most obvious in dry soil. If the hydrogen concentration varies with time as in the case with vegetation, it will become an unknown that may need to be determined to accurately quantify soil moisture content.

The depth of measurement depends on the water content and the amount of lattice water. Hydrogen in soil water or lattice water reduces the intensity of neutrons and the depth of measurement in the soil. That is, average soil water is measured to a greater depth in dry soils and to shallower depth in water or flooded soil. Recently, Franz *et al.* (2012a) presented the following equation to correct for soil lattice water:

$$z^* = \frac{5.8}{\rho_{bd}\tau + \theta + 0.0829}$$

where z^* is effective depth of the CRS probe (cm); ρ_{bd} is soil dry bulk density (g/cm^3); τ is weight fraction of lattice water in the mineral grains and bound water defined as the amount of water released at 1 000°C preceded by drying at 105°C (g water per g dry minerals, herein known as lattice water); and θ is volumetric pore water content (m^3/m^3). This effect is constant for any given soil and thus can be handled in the calibration.

Desilets and Zreda (2013) reported that the footprint of the CRS-1000 probe is inversely proportional to air density, and related linearly to the height of the sensor above the ground, up to a height of 125 m. There is no further impact as the height is increased. Soil moisture content has a small impact on the foot print, whereas atmospheric humidity has significant impact; reducing the foot print by 40 m for every 0.01 kg/kg increase in specific humidity. When quantifying θ_S, the effect of changes in atmospheric pressure (Rivera Villarreyes, Baroni and Oswald, 2011), incoming cosmic ray intensity (Zreda *et al.*, 2012) and atmospheric water vapour (Franz *et al.*, 2012a; Zreda *et al.*, 2012; Rosolem *et al.*, 2013) on neutron counts needs to be accounted for. Other corrections are outlined by Zreda *et al.* (2012).

The probe measures average soil moisture across a large spatial area and consequently, the site needs to be relatively uniform. Complex sites that have many different land uses would present a problem because the average water content of the different systems would be measured. Rivera Villarreyes, Baroni and Oswald, (2013) data highlights this effect as they found the calibration of the CRS-1000 probe to vary during the growing season of sunflower and winter rye. Although the neutron density was corrected for humidity, pressure, and lattice water, the CRS-1000 probe determined that the soil water content varied throughout the growing season. This probably reflects the change in the plant biomass that affects the determination of soil moisture content. The biomass of annual crops were found to change dramatically throughout the growing season and the relative water content in the above-ground vegetation ranged from 98 percent in young plant material (tillering) to 40 percent in mature plants (Teulat *et al.*, 1997). Although the relative water content was high at tillering, the mass of water (expressed on an area basis) in the biomass was low at the early stages of growth and increased significantly until maximum biomass was achieved, and then declined during maturation. For example, if there is a cereal biomass of 10 tons (t) per ha (dry weight), then it is likely to contain 15 t ha of water in the above-ground fresh material. For the purpose of comparison, a soil that has a 0.2 volumetric water content contains 200 t of water per ha in the surface 0.1 m. Thus water in the crop vegetation represents about 7 percent of the amount in the top 0.1 m of soil. Based on current knowledge and predictive capability of crop biomass using models such as the Agricultural Production Systems Simulator (APSIM), it should be possible to develop an algorithm that will correct for water in the biomass.

Because the CRS-1000 probe measures soil moisture content to different depths depending on the wetness of the soil, accurate estimates are difficult to obtain in shrink-swell soils (for example, Vertisol soils; Figure 4). When the soil is wet, the surface increases and at the same time, depth of measurement with the CRS-1000 probe would be reduced. When the soil is dry, the soil retracts (shrinks), the surface contracts and the depth of measurement with the CRS-1000 probe would increase. Although not tested, this could be solved by combining measurements with the CRS-1000 probe and the neutron probe, and using a water balance model coupled with model data fusion to integrate to a depth where there is zero change (Ringrose-Voase *et al.*, 2003).

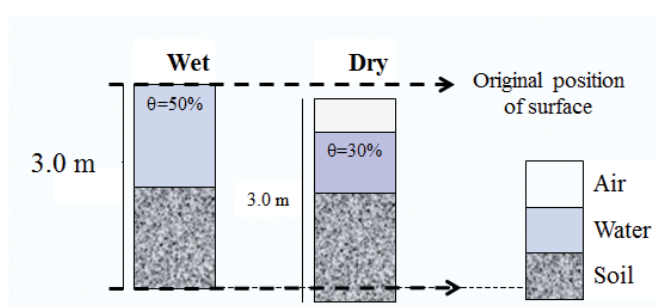

FIGURE 4. Conceptual diagram of the change in the soil surface of a Vertisol under wet and dry conditions.

Early results from the CosmOz network suggest that the CRS-1000 probe is capable of measuring near-surface soil moisture content in a range of soils and climates. The probe's large area sample creates potential uses for applications such as agricultural moisture availability monitoring and catchment scale rainfall-runoff forecasting in environments where antecedent soil moisture influences runoff generation. It may also have potential applications in weather modelling as well as short-term stream flow forecasting, where direct assimilation of ground measured soil moisture can improve forecasting. The larger scale of observation also means that the observations have applications in evaluating landscape-scale mean soil moisture estimates, for example those derived from models or from satellite remote sensing observations.

CONCLUSIONS

Results from the CosmOz network and published literature, confirm that the probes are capable of measuring near-surface soil moisture content in a large scale and in a range of soils and climates. They have the potential for use in: (i) agriculture, (ii) catchment-scale rainfall run off forecasting in environments where antecedent soil moisture influences runoff generation — however, this needs to be further tested to establish whether there are significant improvements in the predictions over the established methods, (iii) water balance assessments, and (iv) validation of soil water content obtained through remote sensing.

The large scale of observation also means that the observations have application in evaluating landscape-scale mean soil moisture estimates. The potential for data/model fusion (i.e. soil water balance coupled with vegetation and land-surface modelling) is exciting although there are some factors that need to be considered when using the probe. A key requirement is the selection of the site so that it matches the foot print of the probe (600 m). This needs to be of uniform land use and relatively uniform soils, as the probe measures average water content over this larger area. Calibration of the probe needs careful attention to include the effect of water stored in the vegetation and soil lattice water. The depth of measurement changes with water content. A cosmic ray probe has significant potential to quantify the average water content across a large area, but this needs to be validated with further research covering a range of soil types, including shrink-swell soil, differing hydrological regimes and different land-uses. Water in vegetation, especially for growing crops, needs to be quantified, and methods to correct for this effect are being developed.

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