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Key Points:

- Cosmic-ray probes estimate soil moisture across diverse soils and landscapes
- Improved correction procedures support a theoretical calibration function
- Differences in calibration parameters between sites support biomass estimation

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Calibration and correction procedures for cosmic-ray neutron soil moisture probes located across Australia

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Abstract The cosmic-ray probe (CRP) provides continuous estimates of soil moisture over an area of ~30 ha by counting fast neutrons produced from cosmic rays which are predominantly moderated by water molecules in the soil. This paper describes the setup, measurement correction procedures, and field calibration of CRPs at nine locations across Australia with contrasting soil type, climate, and land cover. These probes form the inaugural Australian CRP network, which is known as CosmOz. CRP measurements require neutron count rates to be corrected for effects of atmospheric pressure, water vapor pressure changes, and variations in incoming neutron intensity. We assess the magnitude and importance of these corrections and present standardized approaches for network-wide analysis. In particular, we present a new approach to correct for incoming neutron intensity variations and test its performance against existing procedures used in other studies. Our field calibration results indicate that a generalized calibration function for relating neutron counts to soil moisture is suitable for all soil types, with the possible exception of very sandy soils with low water content. Using multiple calibration data sets, we demonstrate that the generalized calibration function only applies after accounting for persistent sources of hydrogen in the soil profile. Finally, we demonstrate that by following standardized correction procedures and scaling neutron counting rates of all CRPs to a single reference location, differences in calibrations between sites are related to site biomass. This observation provides a means for estimating biomass at a given location or for deriving coefficients for the calibration function in the absence of field calibration data.

1. Introduction

Ground-based soil moisture measurements are used in a wide variety of applications including agriculture, hydrology, meteorology, and in the calibration of satellite soil moisture retrieval algorithms, yet the usefulness of traditional point-based soil moisture measurements can be hampered by spatial variability in soil moisture. For example, *Haverkamp et al*. [1998] note that difficulty in modeling soil-water dynamics can arise from the mismatch in scale between field measurement and the scale of model predictions. Often very large numbers of samples are required to reduce the uncertainty in measured values [*Western et al*., 1998]. As much of the variability in soil moisture can occur at a small scale (~1–10 m), measurements at a much larger scale (~100s m), such as that measured by cosmic-ray soil moisture probes (CRPs) [*Desilets et al*., 2010; *Zreda et al*., 2008], would be beneficial to many types of analyses.

CRPs provide continuous estimates of soil moisture over an area of approximately 30 hectares by measuring naturally generated fast neutrons (energy 10–1000 eV) that are produced by cosmic rays passing through the Earth's atmosphere. The neutron intensity above the land surface is inversely correlated with soil moisture as it responds to the hydrogen contained in the soil and plant water and to a lesser degree to plant and soil carbon compounds [*Desilets et al*., 2010]. The cosmic-ray technique is also passive, noncontact, and is largely insensitive to bulk density, surface roughness, the physical state of water, and soil texture (although it is known to have some sensitivity to lattice water which may be correlated to texture) [*Desilets et al*., 2010]. Therefore, the method has several advantages over conventional larger scale approaches based on microwave frequency remote sensing techniques.

CRPs have been used at a range of sites in the USA [*Desilets et al*., 2010; *Franz et al*., 2012b, 2013b; *Zreda et al*., 2012] and Europe [*Bogena et al*., 2013; *Rivera Villarreyes et al*., 2011] and in the places where they have been calibrated, they appear to give reasonably accurate estimates of large-area soil moisture

($\pm$0.02 m^3 m^{-3}) [*Baatz et al*., 2014; *Franz et al*., 2012a; *Zreda et al*., 2012]. The horizontal footprint of the CRP is inversely proportional to atmospheric pressure and independent of soil moisture, such that at sea level, a CRP has a footprint with a diameter of ~600 m [*Desilets and Zreda*, 2013; *Zreda et al*., 2008]. However, the depth of measurement of the CRP depends strongly on soil moisture, in theory, ranging from ~0.7 m in dry soils to ~0.1 m in wet soils [*Franz et al*., 2012b; *Zreda et al*., 2008].

Many of the attributes of CRPs that ascertain its signal strength have been determined experimentally under controlled conditions or modeled based on neutron scattering theory [*Zreda et al*., 2008]. Using neutron particle tracking code, *Desilets et al*. [2010] noted that the neutron flux is not particularly sensitive to the nature of the soil material and derived a calibration function which is independent of soil type, but requires site-specific calibration to determine the counting rate over dry soil [*Zreda et al*., 2008, 2012]. Testing of this calibration function in some studies [*Bogena et al*., 2013; *Franz et al*., 2012b] suggested applicability (i.e., independent of soil type); however, for a site in Germany, *Rivera Villarreyes et al*. [2011] altered the calibration function to derive a soil-specific curve. Further calibrations for a range of soil types and locations are therefore needed to confirm whether or not the theoretical calibration function of *Desilets et al*. [2010] (henceforth referred to as the "Desilets calibration function") is widely applicable or soil specific.

To date, there have been no published calibration studies for CRPs in the southern hemisphere, so in this paper we present the results of extensive analysis undertaken across a network of CRPs established in Australia referred to as the CosmOz network. We describe the standard instrumentation design and characteristics of sites that make up the CosmOz network. Measurement procedures are described, and corrections for effects of atmospheric pressure, vapor pressure changes, and variations in incoming neutron intensity are presented. We assess the magnitude and importance of these corrections and present standardized approaches for network-wide analysis. In particular, we present a new approach to correct for neutron intensity variations and test its performance against existing procedures used in other CRP studies. Using a number of replicate field calibrations across our field sites, we compare sample weighting procedures and the applicability of the *Desilets et al*. [2010] calibration function. We also consider the importance of including additional sources of hydrogen (lattice water and that related to soil organic matter) in the calibration procedure. Finally, we demonstrate the value of standardizing correction and calibration procedures through a network-wide analysis of calibrated sites.

2. Materials and Methods

2.1. Study Sites

Cosmic-ray probe sites were established at nine locations around Australia to form the inaugural CosmOz network (Figure 1 and Table 1). These sites were established between October 2010 and

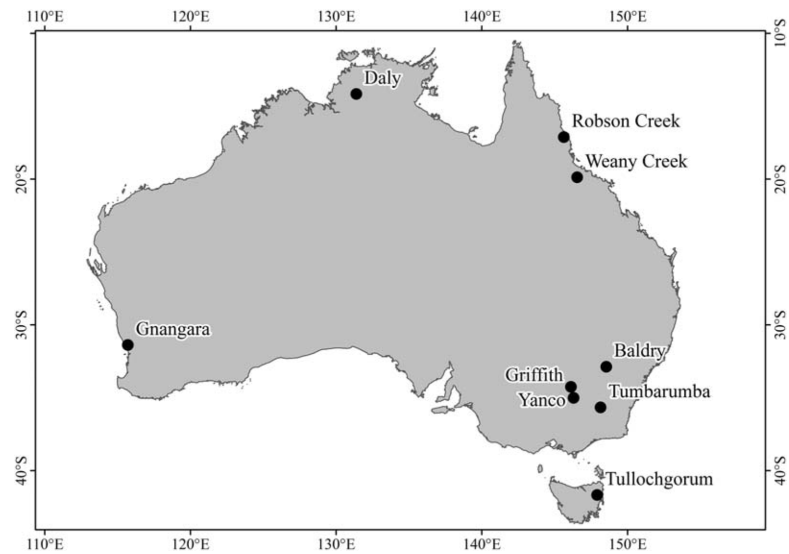

Figure 1. Location of the cosmic-ray probe measurement sites which form the CosmOz network.

Table 1. CosmOz Measurement Site Details Including Site Name, Geographic Location, Elevation, Mean Annual Rainfall, Mean Annual Evaporation, Mean Annual Temperature, Vegetation Cover, Land Use, Above Ground Biomass and Soil Type[a]

Site	Lat./Long.	Elevation (m)	Mean Annual Rain (mm)	Mean Annual PET (mm)	Mean Annual Temp. (°C)	Vegetation Cover/Land Use	Above Ground Biomass (kg m^{-2})	Australian Soil Classification
Baldry	32.87°S/148.54°E	438	618	1684	16.4	Open grassland/grazing	1.1[b]	Chromosol
Daly	14.16°S/131.39°E	75	1445	2372	27.4	Tropical savannah/grazing	6.4[c]	Kandosol
Gnangara	31.38°S/115.71°E	50	649	2017	18.6	Banksia woodland/National park	3.9[c]	Podosol
Griffith	34.25°S/146.12°E	127	406	2085	19.7	Crops/irrigated agriculture	2.1[b]	Kandosol
Robson Creek	17.12°S/145.63°E	715	1300	1644	21.1	Tropical rainforest/National park	42.0[c]	Dermosol
Tullochgorum	41.67°S/147.91°E	285	610	1048	11.7	Improved pasture/grazing	1.1[b]	Sodosol
Tumbarumba	35.66°S/148.15°E	1200	1412	962	9.3	Wet eucalypt forest/State forest	36.7[c]	Kandosol
Weany Creek	19.88°S/146.54°E	287	659	2056	23.3	Open woodland/grazing	2.2[c]	Chromosol
Yanco	35.01°S/146.3°E	124	437	1728	16.6	Open grassland/grazing	0.9[c]	Sodosol

[a]Meteorological data are taken from the nearest Bureau of Meteorology station.
[b]Site measurements.
[c]Satellite estimate [*Liu et al*., 2013; *Lucas et al*., 2010].

June 2011. The sites span a large range of environments with latitudes ranging from 14°S to 42°S, and altitudes ranging from 50 to 1200 m above sea level. The sites represent a large variation in climates from the tropics to temperate areas with mean annual temperatures ranging from 9 to 27°C, mean annual precipitation ranging from 406 to 1445 mm, and mean potential evapotranspiration (PET) ranging from 962 to 2372 mm. Some sites are moisture limited (i.e., PET > rainfall), whereas others are energy limited (i.e., rainfall > PET). A large range of soils from almost pure sand to heavy clay are represented within the CosmOz network.

2.2. Cosmic-Ray Probe Measurement Systems

A standard measurement system design has been used at all CosmOz sites and is shown in Figure 2. The system has a single polyethylene shielded cosmic-ray probe (CRP-1000B, Hydroinnova, Albuquerque, NM, USA), which monitors neutron intensity in the epithermal to fast neutron energy range. The probe is filled with BF_3 gas and interfaces directly to a neutron pulse detector module and an associated data logger (Q-NPM and Q-DL-2100, Quaesta Instruments LLC, Tucson, AZ, USA). The system also measures barometric pressure, internal component temperature, and relative humidity. The standard CosmOz design also includes a 0.2 mm tipping bucket rain gauge (TB3, Hydrological Services Pty Ltd, Sydney, NSW, Australia) and three time-domain reflectometry (TDR) soil moisture probes (CS625, Campbell Scientific, Logan, UT, USA). The TDR sensors were installed vertically to a depth of 0.3 m and were located within a 4 m radius of the CRP. The power for the system was provided by a 12 V, 30 Ah battery which was charged by either a 20 W or 40 W solar panel. The system was programmed to record data at hourly intervals which was sent via satellite telemetry (Iridium SBD services) in near-real-time to a database on a remote server. All components were mounted on a 2 m mounting pole attached to a concrete footing and guyed with steel cable.

2.3. Correcting Neutron Count Measurements

In order to isolate the effect of soil moisture on neutron count measurements, it is first necessary to remove variation due to other environmental factors. The largest correction that is required is an adjustment for changes in atmospheric pressure, but there are also corrections required for changes in atmospheric water vapor and changes in the intensity of the incoming neutron flux. Corrections used by the US-based CRP network (COSMOS) have been documented by *Zreda et al*. [2012]. For the CosmOz network, we use the same corrections for atmospheric pressure and water vapor, but use a different approach to correcting for changes in incoming neutron intensity. Each of these corrections is described below.

2.3.1. Correction for Atmospheric Pressure Variation

Cosmic-ray neutron intensity, and thus neutron count, is particularly sensitive to elevation or the mass of air above the sensor, which is defined as an exponential relationship with barometric pressure [*Zreda et al*., 2008, 2012]

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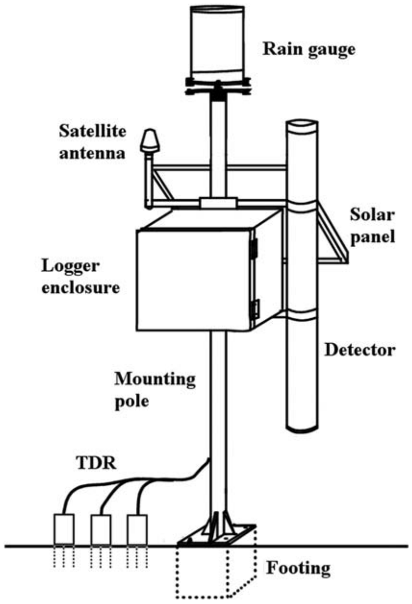

Figure 2. Schematic diagram of a standard CosmOz probe installation.

$$f_P = \exp\left[\beta\left(P - P_{ref}\right)\right] \quad (1)$$

where P is atmospheric pressure (mb) and P_{ref} is the reference atmospheric pressure (mb), which for CosmOz sites is taken as the average atmospheric pressure, which is calculated using standard formulas based on site elevation [*U.S. Standard Atmosphere*, 1976]. β is the atmospheric attenuation coefficient (cm^2 g^{-1} or mb^{-1}) for neutron-generating cosmic rays which has been calculated for each of our sites using the method described by *Desilets et al*. [2006].

2.3.2. Correction for Atmospheric Water Vapor Variation

Water vapor in the atmosphere has the same neutron moderating capacity as water in the soil and as such will influence the total neutron count. A correction factor for atmospheric water vapor effects on CRP measurements was developed by *Rosolem et al*. [2013] using neutron transport modeling and measurement data. This correction factor utilizes near-surface absolute humidity (ρ_{v0}, g m^{-3}), which is derived from measurements of temperature, atmospheric pressure, and humidity [see *Bolton*, 1980]. The correction factor for changes in atmospheric water vapor (f_{wv}) is derived from

$$f_{wv} = 1 + 0.0054\left(\rho_{v0} - \rho_{v0}^{ref}\right) \quad (2)$$

where ρ_{v0}^{ref} is the reference absolute humidity, which we set to 0 g m^{-3} (i.e., dry air) for all CosmOz sites. Using a common reference allows comparisons between sites within the network, which will be discussed later in section 2.3.4. Most CosmOz sites have supplementary measurements of temperature, atmospheric pressure, and humidity and where available these are used. For sites without these measurements, we use daily average meteorological observations from nearby Bureau of Meteorology stations which are derived from the SILO database (http://www.longpaddock.qld.gov.au/silo/). In our analysis, we have assessed whether this latter data set is suited to atmospheric water vapor corrections.

2.3.3. Correction for Incoming Neutron Flux Intensity

CRP data also need to be corrected for variations in incoming neutron flux. The flux of neutrons that reach the Earth's surface is influenced by changes in the intensity of incoming primary cosmic-ray particles. The flux of high-energy secondary neutrons (which are not affected by soil moisture) are measured at neutron monitors [*Simpson*, 2000] which are located around the globe and it is possible to use these measurements to correct CRP data. To account for variations in incoming neutron flux, an intensity correction factor is calculated by normalizing the source intensity to a fixed point in time [*Zreda et al*., 2012]. The correction factor for incoming neutron intensity (f_i) is expressed as

$$f_i = \frac{I_m}{I_{ref}} \quad (3)$$

where I_m is the selected neutron monitor counting rate at any particular point in time and I_{ref} is a reference counting rate for the same neutron monitor from an arbitrary fixed point in time. The reference time for sensors in the CosmOz network is 1 May 2011 (the same date used by the COSMOS network). Both the CosmOz network and US-based COSMOS network access neutron flux data through the Neutron Monitor Database (NMDB; www.nmdb.eu) which provides access to real-time data from a global network of monitoring stations.

A further complicating factor in neutron intensity corrections is the fact that the strength of Earth's magnetic field at a given location also influences neutron flux intensity. At the poles the minimum energy that a particle must have to penetrate the Earth's magnetic field is less than that required near the equator. This minimum energy requirement is described as the cutoff rigidity (R_c) [*Desilets and Zreda*, 2003]. For this reason the neutron flux intensity correction for a location also needs to account for its geomagnetic cutoff rigidity. The way in which the CosmOz network and US-based COSMOS network achieve this differs and are compared in this paper. For the CosmOz network, the NMDB monitor with the closest cutoff rigidity to each CRP station was selected, following the reasoning that such sites will experience similar intensities of neutron flux. The COSMOS network follows a different approach by correcting all probes using one neutron monitor at Jungfraujoch, Switzerland and applying a correction for site cutoff rigidity (R_c)

$$R_{cCorr} = -0.075(R_c - R_{cJUNG}) + 1 \tag{4}$$

where R_{cJUNG} is the cutoff rigidity for the Jungfraujoch neutron monitor (4.49 Gv). This is a working model developed by the COSMOS project based on preliminary analysis of neutron monitor data from locations spanning a large range in R_c. The final cutoff rigidity-based intensity correction for COSMOS (f_{iRc}) has the form

$$f_{iRc} = (f_i - 1)R_{cCorr} + 1 \tag{5}$$

In this paper we compare these approaches to intensity correction at the Tullochgorum CRP site which is within 155 km of the only neutron monitor in Australia. This neutron monitor is at Kingston in Tasmania and is run by the Bureau of Meteorology Space Weather department. The Kingston neutron monitor is not used in routine intensity corrections by the CosmOz network as data are not yet available through the neutron monitor database; however, this does offer a unique opportunity to test different correction approaches.

2.3.4. Scaling to Weany Creek

The counting rates of all probes within the CosmOz network are scaled to our longest running site at Weany Creek. One advantage of correcting the probe network to a single location is that it enables a direct comparison of counting rates between sites. In theory, if all sources of hydrogen within the probe footprint have been accounted for, every site will have the same value for N_0. This will be discussed further in section 3.2.4.

Scaling factors for all probes were calculated using equation (4) from *Desilets et al*. [2006] to estimate an equivalent neutron counting rate compared to that experienced at sea level at the equator. Scaling of the count rate for each site was then achieved by multiplying the raw neutron count by the ratio of the scaling factor for Weany Creek (f_{sw}) to the scaling factor for each site (f_s) as shown in equation (6). A similar scaling is undertaken for the COSMOS network which has adopted a reference station in San Pedro [*Zreda et al*., 2012].

2.3.5. Application of Correction Factors

Final corrected counts (N) were calculated using the following equation:

$$N = N_{raw}\left(\frac{f_P f_{wv}}{f_i}\right)\left(\frac{f_{sw}}{f_s}\right) \tag{6}$$

where N_{raw} is the uncorrected neutron count from the CRP. The first set of brackets includes corrections for atmospheric pressure, water vapor, and neutron intensity while the second set of brackets includes corrections for scaling counts to the Weany Creek reference site. Corrections were applied to data before calibration took place.

2.4. Converting Neutron Counts to Soil Moisture

An increase in soil moisture results in the moderation of neutrons within the soil matrix and causes a decrease in fast neutron intensity above the soil surface. *Desilets et al*. [2010] used the neutron particle code MCNPX [*Pelowitz*, 2005] to develop a function for estimating gravimetric moisture content by measuring fast neutron intensity above the ground. *Dong et al*. [2014] modified this equation to include a correction factor for the effects of lattice water and to report soil moisture in volumetric units. We have modified the *Dong et al*. [2014] calibration function, as shown in equation (7), to also include a correction for the influence of hydrogen held within soil organic matter

$$\theta=\left(\frac{0.0808}{\left(\frac{N}{N_0}\right)-0.372}-0.115-w_{lat}-w_{SOM}\right)\rho_{bd} \quad (7)$$

where N is the corrected neutron intensity, N_0 is the neutron intensity in air above a dry soil (which is obtained from the field calibration, see section 2.4.1), ρ_{bd} is soil bulk density (g cm^{-3}), w_{lat} is the lattice water content (g water per g of soil), and w_{SOM} is soil organic matter expressed as a water equivalent (g of water per g of soil). Analysis by *Desilets et al*. [2010] and *Zreda et al*. [2008] suggest that the shape of the calibration function (i.e., the values of the three numeric coefficients in equation (7)) is similar for different chemical compositions and textures of soil and that a single calibration curve is suitable for converting neutron intensity to soil moisture. In this paper we tested this assumption using field calibration measurements taken across the wide array of environments that make up the CosmOz network.

2.4.1. Field Sampling for Calibration

Cosmic-ray soil moisture probes in the CosmOz network were calibrated using area-averaged soil moisture determined from field sampling campaigns. The calibration involved collection of gravimetric and volumetric soil samples at three distances from the probe (25, 100, and 200 m) along each cardinal and intercardinal direction (i.e., eight radial directions). The radial distances are such that samples cover the measurement footprint of the probe [*Desilets and Zreda*, 2013; *Zreda et al*., 2012] and can be given the same weight; hence, a simple arithmetic average of derived soil moisture can be used. At each sample point, soil cores were taken to calculate gravimetric and volumetric soil moisture content for three depths (0–5, 10–15, and 25–30 cm), giving a total of 72 samples per calibration. Gravimetric water content was determined by drying samples at 105°C for 24 h [*Klute*, 1986]. Volumetric water content was calculated as the product of gravimetric water content and soil bulk density. The depth-weighted (see section 2.4.3) soil moisture from field calibration and corresponding corrected neutron count, between 10:00 am and 4:00 pm on the day of sampling, was used to determine N_0 in equation (7). This strategy, used for the CosmOz network, differs slightly from the standard COSMOS procedure; however, *Zreda et al*. [2012] suggest that the arrangement of samples has little bearing on the calculated average soil moisture when such a large number of samples are collected. To test the validity of the calibration function, we obtained between one and five field calibration points per site covering (as far as possible) the full range of expected soil moisture contents at different CosmOz sites.

2.4.2. Calibration Sample Size Analysis

Using the extensive set of soil moisture samples collected in the field for CRP calibration, it was possible to assess the level of standard error expected in footprint-wide soil moisture estimates and also to assess whether the number of samples taken was appropriate. For calibration data sets from each site we calculated the average of the soil moisture measurements from all depths at each of the 24 sampling points. This set of 24 point averages was then randomly resampled to represent sample sizes ranging from n = 24 to n = 2. For each sample size, 100 unique resampled data sets was compiled which enabled robust estimates of the standard error in soil moisture estimates for the CRP footprint to be made.

2.4.3. Sample Weighting

The effective depth of measurements is known to vary with soil moisture content [*Franz et al*., 2012a, 2012b; *Zreda et al*., 2008]. This suggests that samples should be weighted with depth to obtain a more accurate calibration of the CRP. Two such approaches exist for calculating depth weighting of samples. One of these methods was proposed by *Franz et al*. [2012b] and is a linear weighting with depth that depends on the effective depth of measurements (see section 2.4.5), which is calculated for the time of calibration. The second approach is that developed by D. Desilets (unpublished data, 2010), which is a product of exponential functions, representing the production and absorption of neutrons in dry and wet soil layers [*Franz et al*., 2012a]. In this paper, the average soil moisture content of the 24 samples collected from within each depth increment (see section 2.4.1) are used to compare both depth-weighting approaches.

2.4.4. Including Other Sources of Hydrogen

Hydrogen is also found in mineral structures (lattice water) and organic material within soil. *Zreda et al*. [2012] and *Franz et al*. [2013a] suggest that these additional pools of hydrogen may have a significant influence on counting rates and, therefore, should be incorporated into the calibration process used for calculating N_0. We explored the effect of including these additional sources of hydrogen in the site calibration procedure. Using the same definition as *Franz et al.* [2012b], lattice water is defined as the amount of water released at 1000°C preceded by drying at 105°C. A subset of soil samples from each CosmOz site were analyzed for lattice water (w_{lat}) at the ACTLABS laboratory in Canada and for total organic carbon (TOC) by Heanes wet oxidation, method 6B1 in *Rayment and Higginson* [1992] at the SGS Environmental Services laboratory in Cairns, Australia.

Following *Franz et al.* [2013b] and *Bogena et al.* [2013], we convert soil organic matter (assumed to be cellulose, $C_6H_{10}O_5$) into an equivalent amount of water (w_{SOM}) by multiplying the weight of TOC by 0.556, which is the ratio of 5 times the molecular weight of water to the molecular weight of cellulose. The factor of 5 is included because there are 10 hydrogen atoms per molecule of cellulose but only 2 per water molecule.

2.4.5. Calculation of Effective Measurement Depth

Water storage in the upper soil layers (W_s) can be calculated from volumetric soil moisture content, θ, if the depth to which the value of θ applies is also known. A calibrated CRP gives a single value of θ at any particular time and the depth to which this applies varies with moisture content. *Franz et al.* [2012b, 2013a] derived an equation for estimating the effective sensor measurement depth (z^*)

$$\varphi(z^*)=W_s+\int_0^{z^*}\frac{\left(\rho_{bd}(z)(w_{lat}+w_{SOM})+\theta(z)\right)}{\rho_w}dz \quad (8)$$

where $\varphi(z^*)$ is the 86% cumulative depth sensitivity (herein referred to as z^*), ρ_{bd} is the dry bulk density of the soil (g cm^{-3}), and ρ_w is the density of liquid water (assumed to be 1 g cm^{-3}). Equation (8) has been modified from its original form in *Franz et al.* [2012b] to also include w_{SOM}.

3. Results

3.1. Correcting Neutron Count Measurements

Site-specific constants used to calculate the correction factors for pressure, humidity, and incoming neutron flux intensity are shown in Table 2. The range of each correction factor was calculated for the 2012 calendar year, which is the first year that all CosmOz sites had completed at least one calibration. Examples of each calibration factor are discussed in more detail in the sections below.

3.1.1. Correction for Atmospheric Pressure Variation

The correction factor for changes in atmospheric pressure has the largest range of the three corrections applied. For the CosmOz network, this ranged between 0.87 and 1.05 (approximately ±9%) at the Daly site and 0.81 and 1.20 (approximately ±20%) at Tullochgorum. These sites represent the respective lower and

Table 2. Correction Factors for Each CosmOz Site[a]

Attribute	Baldry	Daly	Gnangara	Griffith	Robson Creek	Tullochgorum	Tumbarumba	Weany Creek	Yanco
Reference pressure (mb)	961	1004	1007	997	930	979	878	978	998
Atmospheric attenuation coeff. (mb^{-1})	0.0075	0.0070	0.0075	0.0075	0.0071	0.0076	0.0076	0.0072	0.0075
Pressure correction range	0.89–1.13	0.87–1.05	0.88–1.18	0.86–1.18	0.91–1.10	0.81–1.20	0.86–1.11	0.88–1.08	0.86–1.19
Water vapor correction range	1.03–1.10	1.02–1.13	1.03–1.11	1.03–1.11	1.03–1.11	1.02–1.09	1.01–1.08	1.02–1.12	1.03–1.10
Cutoff rigidity (GV)	4.7	12.7	4.7	4.1	11.5	2.1	3.7	10.5	3.8
Neutron monitor site	JUNG (4.50 GV)	ATHN (8.53 GV)	JUNG (4.50 GV)	LMKS (3.84 GV)	ATHN (8.53 GV)	YKTK (1.65 GV)	LMKS (3.84 GV)	ATHN (8.53 GV)	LMKS (3.84 GV)
Reference neutron monitor intensity (c h^{-1})	159	56	159	452	56	215	452	56	452
Intensity correction range	0.87–1.04	0.95–1.05	0.87–1.04	0.86–1.06	0.95–1.05	0.84–1.03	0.92–1.06	0.95–1.05	0.86–1.22
Average corrected counts (c h^{-1})	1606	761	1526	847	764	1402	1601	841	1164
Average counting uncertainty (%)[b]	2.5	3.6	2.6	3.4	3.6	2.7	2.5	3.4	2.9
Scaling factor	1.34	0.63	0.94	1.04	1.14	1.29	2.70	0.84[c]	1.05

[a]Ranges are calculated from 12 months beginning 1 January 2012.
[b]In Poisson statistics [*Knoll*, 2010], the variance is equal to the number of counts (N); therefore, the coefficient of variation is $N^{-0.5}$.
[c]Scaling reference site.

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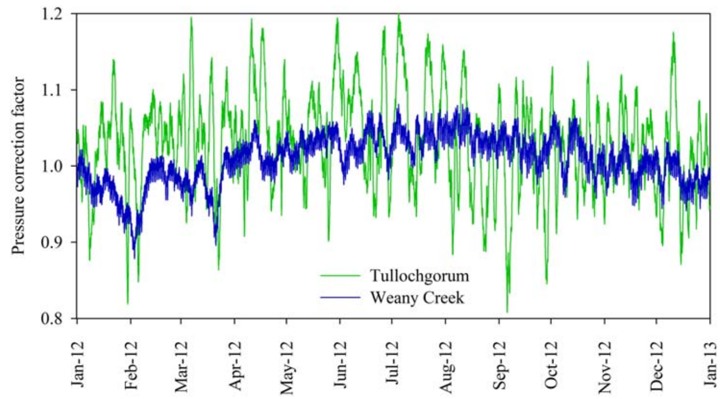

Figure 3. Time series of pressure correction factors for 2012 at Tullochgorum and Weany Creek sites.

upper latitudinal bounds for the CosmOz network. Figure 3 shows the pressure correction factors for Weany Creek, another low-latitude site, and Tullochgorum for the 2012 calendar year. The change in magnitude of pressure correction factors at Tullochgorum is consistently larger than for Weany Creek, which reflects the dynamic nature of the weather systems affecting the higher-latitude site. A seasonal pattern can be seen at Weany Creek, where large, low-pressure systems related to the summer monsoon season appear in late January/early February and March 2012. These typically result in the largest correction factors experienced at this and the two other low-latitude sites.

3.1.2. Correction for Atmospheric Water Vapor Variation

The range of the correction factor for variations in atmospheric water vapor across all sites is between 1.01 and 1.13. Although the variation in correction factor range between sites is smaller than for the pressure correction factor; the dynamic application between sites varies greatly. The seasonal variations in water vapor correction for the Daly site, which is in the tropics, and the temperate Yanco sites are shown in Figure 4. Both sites have hourly temperature and humidity data records which have been used for this example. The range of correction factors are similar at both sites, however, a strong seasonal pattern exists for the Daly site which has distinct wet and dry seasons. Between October and March the water vapor correction is elevated due to the hot, humid, tropical air mass.

For sites without local temperature and humidity data the best available data in Australia is likely to be the SILO weather station database, which provides an estimate of mean daily temperature and humidity. A comparison between vapor corrections for Weany Creek over 12 months using site data and SILO data is shown in Figure 5. Both approaches capture the seasonal changes well with higher corrections in the warmer, humid months. There are periods where the SILO vapor correction factor is higher than that of the

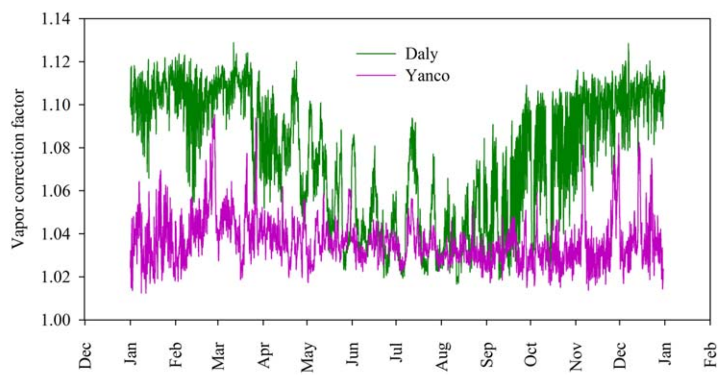

Figure 4. Time series of atmospheric water vapor correction factors over an annual cycle for the Daly and Yanco sites.

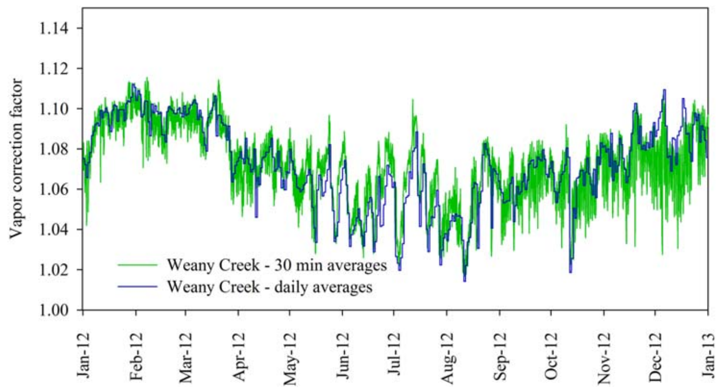

Figure 5. Comparison of water vapor correction factors using daily averages from SILO climate database and 30 min measurements made on-site at Weany Creek.

local data (e.g., ∼5% difference during November–December 2012); however, the vapor correction factor is already the smallest of the three corrections required, and this should not introduce large errors to the estimates of soil moisture. To summarize, in the absence of local data daily average SILO data may be used to represent seasonal changes in vapor pressure, but local high-time resolution data are preferable to capture detailed variability on a subdaily time scale. The most accurate correction for atmospheric water vapor will be obtained from local data collected on the same interval as neutron counting. As such, all CosmOz sites are currently being upgraded with auxiliary temperature and humidity sensors.

3.1.3. Correction for Incoming Neutron Flux Intensity

Figure 6a shows the neutron intensity correction factors calculated over a 12 month period for Tullochgorum based on three methods: (1) local measurements at the Kingston neutron monitor which are used as a datum for comparing methods, (2) the proposed CosmOz method, which uses the NMDB site with nearest R_c (YKTK), and (3) the method used across the US COSMOS network (i.e., JUNG scaled by R_c). The three sets of correction factors show similar trends through time although some variability in intensity correction factors is evident. The effect this variability has on corrected neutron counts is shown in Figure 6b, where the difference in corrected counts from the proposed CosmOz and COSMOS methods as compared to the Kingston correction are shown. Both methods produced close representation of the Kingston correction, including for extreme events such as the solar flare that occurred during March 2012; however, there was less variability in corrected counts using the CosmOz method.

Although calibration procedures have not yet been discussed, it is worth considering at this stage of our analysis what the potential impact of the choice of intensity correction method on derived soil moisture estimates might be and this is shown in Figure 6c. For the 12 month period, soil moisture estimates using the proposed CosmOz method has an average difference 0.012 m^3 m^{-3} from the datum estimates with a RMSE of 0.16 m^3 m^{-3}. Estimates of soil moisture from the COSMOS method showed more variability but estimates were also a good match to the datum with an average difference of 0.015 m^3 m^{-3} and a RMSE of 0.20 m^3 m^{-3}. While differences between the two methods are not great, the CosmOz method provided slightly better estimates, and hence we have chosen this approach across our network of CRP probes. With this in mind though we do acknowledge the operational advantages that can be achieved by correcting an entire network of probes to a single neutron monitor and recommend further investigation be conducted in this area. The neutron monitor from NMDB.eu, which is selected for each CosmOz site is shown in Table 2 as is the magnitude of neutron intensity corrections. These neutron intensity corrections varied from around ±5% (0.95 and 1.05 for ATHN) to ±10% (0.86 and 1.06 for LMKS) across the network.

3.1.4. Corrected Counts

Neutron counting rates for the CosmOz sites tended to increase with latitude (Table 2) and as a result the uncertainty in these counting rates is reduced. The effect of altitude is also demonstrated by comparing counting rates at Yanco and Tumbarumba which have similar latitudes but altitudes of 124 and 1200 m. The higher altitude at Tumbarumba results in average counting rates of 1601 c h^{-1} compared to 1164 c h^{-1} for Yanco. Scaling factors (f_s) for all sites are between 0.63 at Daly and 2.70 at Tumbarumba.

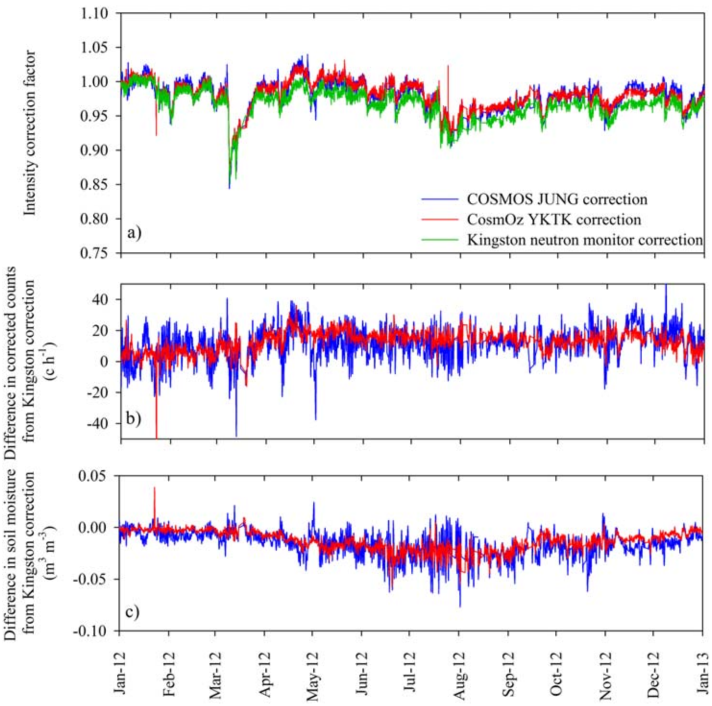

Figure 6. (a) Cosmic-ray neutron intensity correction factors at Tullochgorum using local Kingston neutron monitor (baseline case) and comparison with correction factors using CosmOz approach (nearest cutoff rigidity neutron monitor from NMDB.eu; i.e., Yakutsk, YKTK) and COSMOS approach using neutron monitor measurements from Jungfraujoch (JUNG) scaled by rigidity cutoff. Difference in corrected counts (b) and soil moisture estimate (c) at Tullochgorum using CosmOz and COSMOS approaches when compared to the corrected counts using the Kingston neutron monitor.

3.2. Converting Neutron Counts to Soil Moisture

Average bulk density, w_{lat}, and w_{SOM} for each site are given in Table 3. Soil bulk density varied from 0.95 g cm^{-3} at the forested Tumbarumba site to 1.66 g cm^{-3} at Weany Creek. Bulk density is used for the calculation of volumetric soil moisture as well as to determine the effective depth to which the CRP measures at a given moisture content. The lowest w_{lat} was 0.000 g g^{-1} (below detection) at the sandy Gnangara site and the highest was 0.270 g g^{-1} at Tullochgorum. Sandy soils (Daly, Gnangara) had the lowest w_{SOM} while forested sites (Robson Creek, Tumbarumba) had the highest. The range of w_{SOM} was 0.002 to 0.021 g g^{-1}. Most sites had more than one calibration completed with five completed at Weany Creek. The range of average N_0 values was between 1009 and 1488 c h^{-1} with coefficients of variation, for sites with more than one calibration, between 1.3% and 10.5% (Table 3). Average measurement depths (z^*) ranged between 10 and 35 cm. The minimum depth of measurement was 6 cm at Baldry, Tullochgorum, and Tumbarumba; however, this extended down to 15 cm at the Daly site. The maximum depth of measurement was 46 cm at

Table 3. Bulk Density (ρ_{bd}), Lattice Water (w_{lat}), Soil Organic Matter Expressed as a Water Equivalent (w_{SOM}), Average N_0, and the Range of Effective Depth Measurements for Each Site in the CosmOz Network[a]

Site	ρ_{bd} (g cm^{-3})	w_{lat} (g g^{-1})	w_{SOM} (g g^{-1})	Average N_0 (c h^{-1})	CV N_0 (%)	No. of Calibrations	Average z^* (cm)	z^* Range (cm)
Baldry	1.37	0.028	0.008	1488	n/a	1	20	6–33
Daly	1.48	0.007	0.002	1168	5.3	2	35	15–46
Gnangara	1.42	0.000	0.002	1365	10.5	3	n/a	n/a
Griffith	1.35	0.043	0.006	1233	n/a	1	16	11–21
Robson Creek	1.14	0.050	0.018	1010	8.9	2	12	7–23
Tullochgorum	1.36	0.270	0.011	1333	1.5	3	21	6–31
Tumbarumba	0.95	0.052	0.021	1009	n/a	1	10	6–14
Weany Creek	1.66	0.025	0.006	1170	2.9	5	23	9–32
Yanco	1.60	0.044	0.003	1301	1.3	3	19	9–26

[a]The coefficient of variation (CV) in N_0 is derived from the variation in N_0 from each calibration at a site.

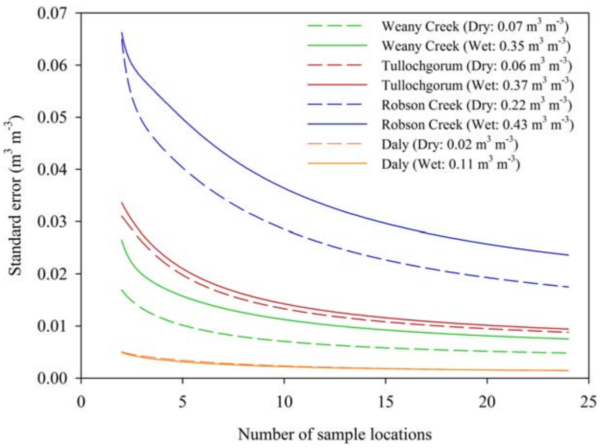

Figure 7. Effect of sample size on standard error in soil moisture estimates.

the Daly site with the shallowest at 14 cm from the forested Tumbarumba site. The values of z^* for Gnangara are not presented for reasons which are discussed below in section 3.2.3.

3.2.1. Field Sampling for Calibration

Figure 7 shows the effect of sample size on the standard error in soil moisture estimates calculated for four CosmOz CRPs. Standard errors have been calculated for the driest and wettest calibration sets at each site. For all sites the vast majority of the reduction in sample standard error occurs well before the 24 samples points which are collected as standard across the CosmOz network. All sites except Robson Creek have a standard error in soil moisture of 0.01 $m^3\ m^{-3}$ or less for a sample size of 24. This suggests that most of the variability in soil moisture is being captured by our sampling design and that standard error would not be reduced much beyond this point with further sampling. Variability increases more rapidly below 15 sample points, and within sites there is a general trend where less variability occurs during dry conditions compared to wet conditions. The lowest variability occurred at the sandy, Daly site, and the highest was found at the Robson Creek rainforest site. The Robson Creek CRP had the largest standard error of any site, irrespective of the number of samples. This site is located in an undulating tropical rainforest and may reflect the high spatial variability in soil moisture encountered in these environments. Figure 7 also demonstrates that there is little difference in soil moisture estimates derived from an 18 (COSMOS) or 24 (CosmOz) point sampling strategy. This figure may be used to determine the number of sample locations required to meet an acceptable, predefined standard error.

3.2.2. Sample Weighting

A comparison of the depth-weighed soil moisture estimates for all calibrations using both the *Franz et al.* [2012a] (linear depth-averaging) and D. Desilets (unpublished data) (exponential depth-averaging) approach is shown in Figure 8. This comparison shows there is a very strong agreement between the two methods over the range of soil moisture contents experienced across the sites. Analysis by *Franz et al.* [2012a] also suggested there was little difference between his method and that of Desilets and our analysis here strongly supports this. The simpler *Franz et al.* [2012a] weighting function has now been adopted by the CosmOz network as the standard depth-weighting procedure.

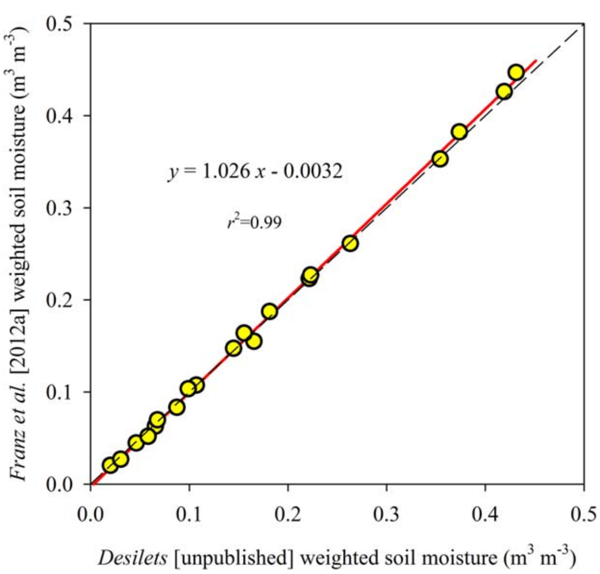

Figure 8. Comparison of calculated soil moisture contents using D. Desilets (unpublished data) and *Franz et al.* [2012a] depth-weighting approaches.

3.2.3. Including Other Sources of Hydrogen

Zreda et al. [2012] and *Franz et al.* [2012b] discuss how the presence of lattice water and soil

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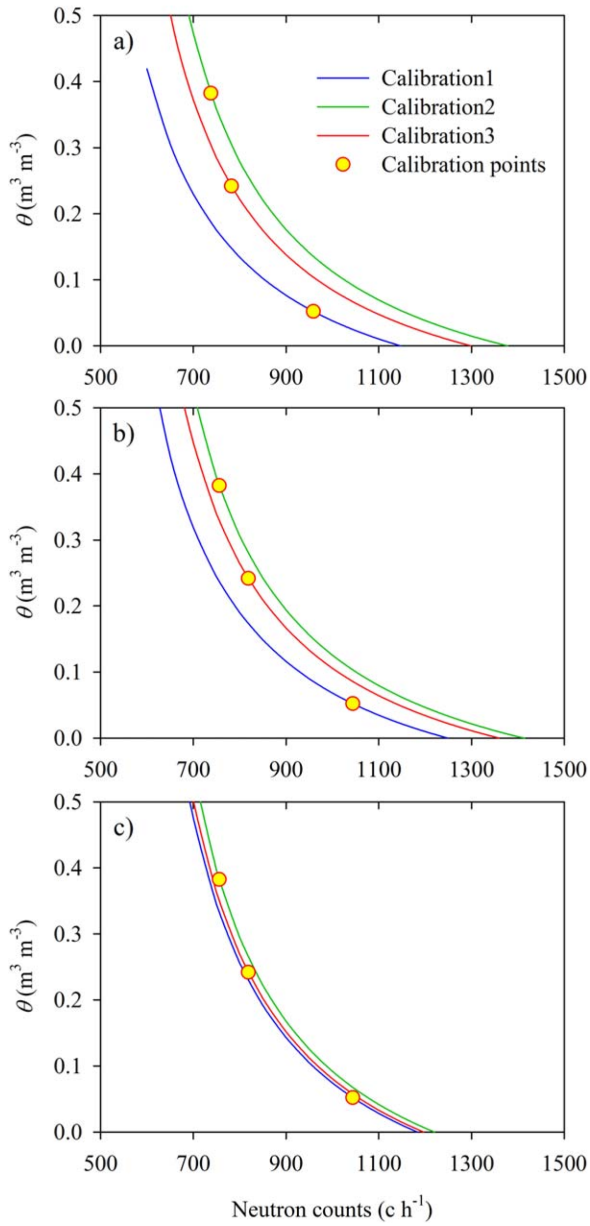

Figure 9. Calibration functions for the Tullochgorum site using equation (7) with (a) no count corrections or additional hydrogen sources, (b) corrections included but no additional hydrogen sources, and (c) all corrections applied and hydrogen sources ($w_{lat}+w_{SOM}$) included.

organic material causes a shift in the shape and slope of the Desilets calibration function. We have found that this is also true for soils in Australia. As an example, three calibration campaigns were conducted at Tullochgorum between July 2011 and July 2013 covering the range of soil moisture conditions between very dry (0.05 m^3 m^{-3}) and saturated soil (0.38 m^3 m^{-3}). Figure 9 shows the calibration curves for each of the three calibrations where individual N_0 values were calculated using equation (7) with (a) no count corrections or additional hydrogen sources, (b) corrections included but no additional hydrogen sources, and (c) all corrections applied and hydrogen sources included. This shows the importance of including the various corrections and other sources of hydrogen in calibrations. Calibration curves calculated using uncorrected neutron counts (Figure 9a) have N_0 values ranging between 1111 and 1334 c h^{-1} and are widely separated. This separation reduces when neutron counts have been corrected for changes in atmospheric pressure, water vapor, and incoming neutron flux (Figure 9b); however, there are still significant differences in the N_0 values (1209–1368 c h^{-1}), especially for the dry calibration curve. When we use equation (7) with w_{lat} and w_{SOM} included the three N_0 values only differ by 42 c h^{-1}, and the three individual calibration curves are very similar (Figure 9c). Similar analysis at other CosmOz locations also found that individual calibrations collapsed to a single curve when the various corrections and other sources of hydrogen were accounted for. This is demonstrated in Table 3 by the sites with a low coefficient of variation associated with the average N_0 values. There are also two sites (Gnangara and Robson Creek) where the variation in N_0 values between different calibrations was comparatively large.

The calibration function, equation (7), did not perform as well at Gnangara (Figure 10), one of the driest CosmOz monitoring locations. At this site the very sandy soil results in low soil moisture content, rarely exceeding 0.08 m^3 m^{-3} and frequently below 0.02 m^3 m^{-3}. It has been acknowledged that the Desilets calibration function does not work well at such low soil moisture values [*Bogena et al.*, 2013; *Desilets et al.*, 2010; *Zreda et al.*, 2012], but the suggestion is made that for the majority of soils, the presence of lattice water alone

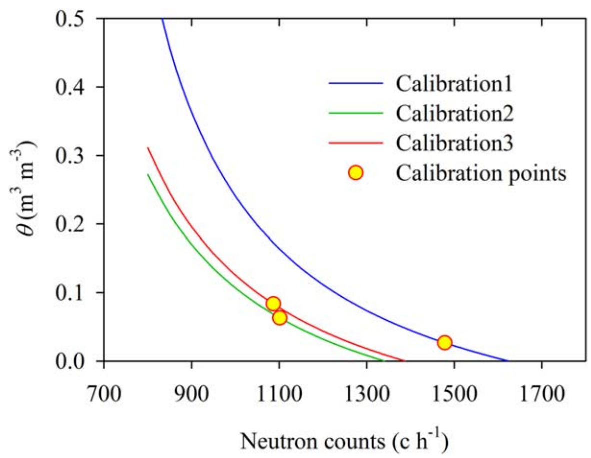

Figure 10. Calibration functions for the Gnangara site using equation (7) with all corrections applied and hydrogen sources ($w_{lat} + w_{SOM}$) included.

would prevent such problems from occurring [*Zreda et al.*, 2012]. However, at Gnangara lattice water was below detectable limits. Hence for this site the calibration function works for the higher soil moisture contents ($\sim$0.08 m^3 m^{-3}) but not for the very low moisture content ($\sim$0.02 m^3 m^{-3}). The latter discrepancy may well be due to the fact that at very low soil moisture contents, uncertainty in neutron counting may result in a soil moisture uncertainty that is similar to the soil moisture value. *Bogena et al.* [2013] showed that this uncertainty can be reduced by increasing the integration period of neutron counting and such an approach would be well suited to the Gnangara site.

The Robson Creek site also had a large coefficient of variation associated with the calculation of N_0. Our analysis of errors associated with sampling in section 3.2.1 suggests that there is a high spatial variability at this site. Robson Creek is located within a mature tropical rainforest which *Desilets et al.* [2010] suggests can reduce the probes sensitivity by 20% which, according to Poisson statistics, increases uncertainty in counting rates. Sampling of soil material in such environments is also hampered by root mats and thick litter. *Bogena et al.* [2013] describe how the dynamic nature of the water content of leaf litter on the forest floor, water intercepted by the forest canopy, and open water in drainage channels can reduce measurement accuracy if not able to be accounted for. These factors could also contribute to the larger uncertainty in N_0 at Robson Creek.

3.2.4. Relationship Between N_0 and Biomass

One advantage of correcting the probe network to a single location is that it enables a direct comparison of counting rates between sites. In theory, if all sources of hydrogen within the probe footprint have been accounted for, every site will have the same value for N_0. From Table 3 we can see that this is not the case. We have accounted for atmospheric pressure, incoming neutron flux intensity, atmospheric water vapor, and water present as w_{lat} and w_{SOM}, but no correction for biomass has been included. Biomass represents another source of hydrogen in the CRP footprint which will affect counting rates. This effect has been demonstrated recently by *Franz et al.* [2013b] where the difference in counting rates in a Ponderosa Forest and nearby cleared area was related to stand biomass and that variations in counting rate in a growing maize crop could be related to biomass.

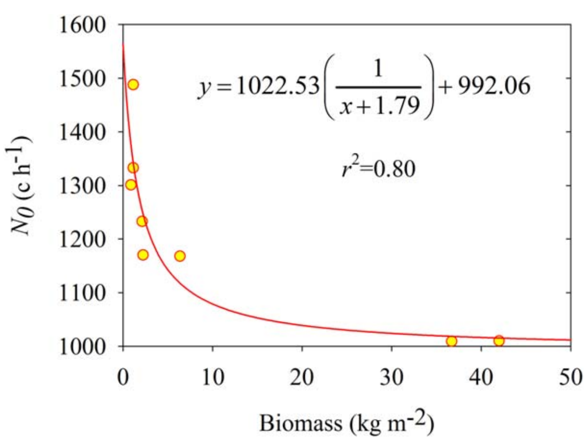

Figure 11. Relationship between biomass and N_0 across the CosmOz network.

This suggests that the derived variation in N_0 values for our sites is related to site biomass. Figure 11 shows the relationship between site biomass and calculated N_0 from Table 3 (excluding Gnangara). The plot shows that biomass can explain 80% of the variation in observed differences in site N_0. The shape of the curve fitted to the data points has that same mathematical form as that used for the calibration function and from where this curve crosses the *y* axis we can get an estimate of N_0 for dry soil and no biomass, which for our case is 1563 c h^{-1}. From the derived curve it is then possible to get a first-order approximation of the biomass at a site and, conversely, if biomass is known for a particular location, then it may be possible to estimate N_0 without performing a standard soil calibration. If w_{lat} and w_{SOM} have been determined, soil moisture can then be estimated using equation (7) where the contribution of those two additional hydrogen sources is subtracted. If required, a matching curve which expresses biomass in water equivalent units (e.g., mm of water) can also be produced.

This relationship shown in Figure 11 presents some interesting areas of future research. For example, it could be used as an alternative to the *Franz et al*. [2013a] Universal Calibration Function for the use of mobile neutron detectors using spatial maps of biomass, w_{lat} and w_{SOM}. It may also be possible to account for the effect of changing biomass on N_0, which would enable the soil moisture signal from under fast-growing crops to be isolated. Allometric techniques may then be employed to determine a time varying N_0 based on a simple proxy such as crop height.

4. Conclusions

We have demonstrated the robustness of the methods employed by the CosmOz network for calibration of CRPs and shown the importance of a number of corrections applied to improve soil moisture estimates. This clearly shows that accurate estimates of soil moisture are dependent on the careful application of a series of important atmospheric and incoming neutron flux intensity corrections. The atmospheric corrections are derived from readily available weather data at each site. Incoming flux intensity variations can be obtained from a limited number of neutron monitoring stations around the globe (mostly in the northern hemisphere), and we have demonstrated that matching locations with neutron monitoring stations with similar a similar cutoff rigidity provides accurate corrections for intensity fluctuations, and hence, robust estimates of soil moisture. Scaling of intensity fluctuation using a rigidity cutoff correction applied to a single station also provided accurate corrections although slightly more variation in estimates was observed.

We have also shown the importance of corrections for lattice water and soil organic matter (expressed as water equivalent). It is only when these corrections are included that we find that the theoretical soil calibration curve applies across a wide range of soil types. The most difficult soils on which to use the CRP are very sandy soils, with low soil moisture ($<$0.02 m^3 m^{-3}), low concentrations of lattice water and soil organic matter, and low neutron count rates. In these soils, it will be necessary to use longer neutron count integrations times ($\sim$days) to obtain reasonable estimates of soil moisture.

The application of standard procedures for calibration, correcting counts then scaling measurements to a single reference location, provides the ability to compare counting rates and calibration coefficients (N_0) across an entire continental network and potentially around the globe. The rigorous application of these standardized procedures at numerous sites has unveiled a relationship between N_0 and biomass. This relationship has many potential new applications such as quantifying biomass and for accounting for biomass when monitoring soil moisture in fast-growing crops. The approach may also have application in mobile CRP measurements if reliable spatial variations in biomass can be obtained. Conversely, if biomass is known then it should be possible to determine N_0 without the need to calibrate against the local soil. However, it would be prudent to carry out further simultaneous soil calibrations and biomass measurements to see how robust the current relationship between N_0 and biomass is.

The CRP has been shown to be unique in its ability to provide large-area ground-based surface soil moisture measurements in a wide range of soil types and climatic regions of Australia. This opens up a number of exciting applications of this device ranging from direct measurements of surface and subsurface water content for data assimilation into numerical weather prediction models or any other process-based model requiring soil moisture information. For example, flood-forecasting models could then benefit from the improvements to weather predictions as well as important data on antecedent surface moisture (which affects runoff) and even surface runoff itself. Applications in agriculture abound, where data on surface moisture could be used to condition dry land and irrigated crop water use and growth models. There are also potential applications in fire risk forecasting since the CRPs can give direct measurements of the dryness of the surface vegetation and litter layers. Having demonstrated the robustness of the method within the CosmOz network, these applications and others can proceed with confidence in this new technique.

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