Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays

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[1] Fast neutrons are generated naturally at the land surface by energetic cosmic rays. These "background" neutrons respond strongly to the presence of water at or near the land surface and represent a hitherto elusive intermediate spatial scale of observation that is ideal for land surface studies and modeling. Soil moisture, snow, and biomass each have a distinct influence on the spectrum, height profile, and directional intensity of neutron fluxes above the ground, suggesting that different sources of water at the land surface can be distinguished with neutron data alone. Measurements can be taken at fixed sites for long-term monitoring or in a moving vehicle for mapping over large areas. We anticipate applications in many previously problematic contexts, including saline environments, wetlands and peat bogs, rocky soils, the active layer of permafrost, and water and snow intercepted by vegetation, as well as calibration and validation of data from spaceborne sensors.

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1. Introduction

[2] A major challenge in land surface studies is to measure water content at a scale representative of spatially averaged physical and biological processes. The need for appropriately scaled measurements has grown recently, in large part because of the increased role of numerical models in weather, climate and hydrologic forecasts [*Western et al.*, 2002]. The measured values of key land surface variables, such as snow water equivalent depth, soil water content and biomass, depend strongly on spatial scale of observation, but upscaling small-volume and downscaling large-volume measurements to the element size of predictive numerical models has remained problematic [*Blöschl*, 2001]. This problem is compounded by the gap between the two main sources of observational data: large-scale remote sensing images with a footprint extending to tens of kilometers and penetration depth of millimeters to centimeters, and invasive measurements of water content at a point in a spatially variable field [*Robinson et al.*, 2008]. The crucial need for hydrologic observations that correspond to the water content at the scale of an irrigated field, a small watershed or a hydrometeorologic model element has not been satisfied with conventional technologies.

[3] Our data show that measurements of ambient neutron fluxes are an excellent proxy for land surface water in liquid or solid state. These ambient neutrons are generated primarily by interactions of secondary cosmic ray neutrons with terrestrial and atmospheric nuclei (Figure 1). The method is based on the dominant role that hydrogen, by virtue of its low mass and large elastic scattering cross section, plays in moderating neutrons as they diffuse through the ground. By measuring the intensity of neutrons generated by cosmic rays near the land surface and slowed through collisions with hydrogen, the effective neutron moderating power of the shallow subsurface can be determined. Because hydrogen in water molecules dominates the moderating power of earth materials even when present in small amounts (<0.02 cm^3 cm^{-3}), water content near the land surface can be inferred directly from neutron fluxes.

[4] The unique neutron scattering properties of hydrogen are well known, and form the basis of neutron soil moisture meters that have been used reliably for decades [e.g., *Holmes*, 1956]. Cosmic ray neutrons have also been applied to hydrology [*Kodama and Nakai*, 1979; *Avdyushin et al.*, 1988], but the proposed techniques were invasive and therefore averaged over small volumes (centimeters to decimeters around the probe). The effect of soil moisture on cosmic ray neutron intensity above the ground surface was identified in measurements made over four decades ago [*Hendrick and Edge*, 1966] but was considered noise in the measurement of neutrons. More recently, applications to hydrology have been recognized [*Zreda et al.*, 2008].

[5] In a previous paper [*Zreda et al.*, 2008] we described the application of the cosmic ray technique to the field-scale determination of soil moisture content at a grassland site in southeastern Arizona, USA. Fixed monitoring stations similar to that one are now being implemented in COSMOS (Cosmic Ray Soil Moisture Observing System; cosmos.hwr.arizona.edu), a network of sensors that will eventually extend across the continental U.S. In this paper we discuss how similar technology can be used for other purposes, for example in determining snow water equivalent depth at the field scale, and distinguishing snow events from soil wetting rain events using measurements in two energy bands. We also suggest other new applications of the cosmic ray technique,

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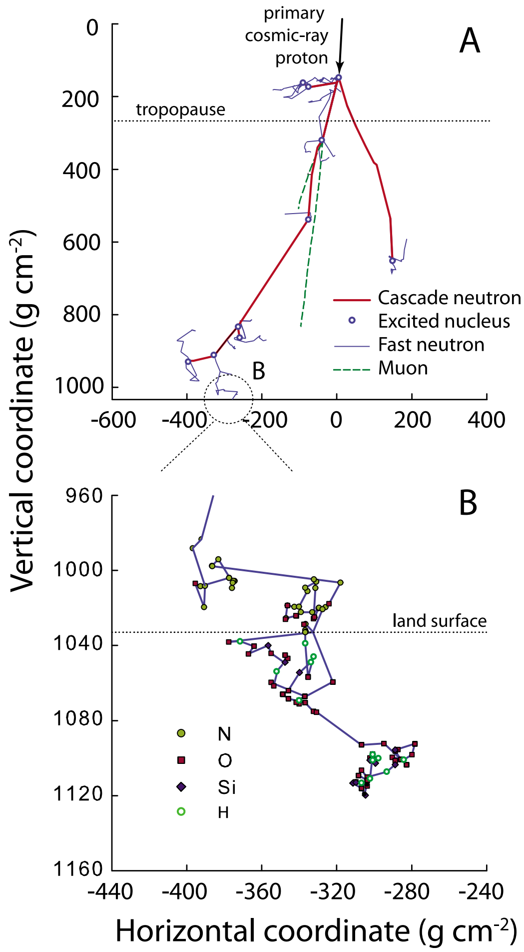

Figure 1. Particle tracks from a cascade simulated with the radiation transport code Monte Carlo N-Particle Extended (MCNPX) [*Pelowitz*, 2005]. Coordinates are in mass shielding units (distance multiplied by density). (a) A 10 GeV primary cosmic ray proton collides with nitrogen in the upper atmosphere, triggering a chain reaction that propagates to sea level. Fast neutrons are generated at each collision marked by a circle. Particle tracks are shown for energies above 1 MeV. (b) A fast neutron unleashed near sea level is scattered elastically in the air and ground and eventually is captured by hydrogen.

such as biomass determinations, and new modes of operation, such as roving soil moisture surveys. Advances in this technology promise to expand both observational capabilities and opportunities for novel research in land surface hydrology.

2. Operational Advantages

[6] The cosmic ray neutron method offers several practical advantages over conventional approaches to measuring land surface water. It is passive, noncontact, and is insensitive to soil texture, bulk density, surface roughness or the physical state of water. It is inherently less sensitive to interference by vegetation than optical or microwave remote sensing techniques. This in part because the attenuation coefficient for fast neutrons (~0.01 m^{-2} kg in water [*Murray*, 2009]) is an order of magnitude smaller than the analogous attenuation coefficient in vegetation (b parameter) for the L band (1.4 GHz) microwave [e.g., *Wigneron et al.*, 2004], and in part because vegetation can itself be a significant source of electromagnetic emissions [*Wigneron et al.*, 2003] but not neutron emissions.

[7] The technique has several other favorable characteristics. The instrumentation is portable and physically robust, with moderate power demands (~1 W) and low data processing and transmission requirements (<1 KB d^{-1}), making practical field campaigns, aerial surveys, and long-term monitoring at remote sites using inexpensive satellite telemetry options. The sample depth, which is related to the collision mean free path and energy loss per collision in soil, is integrated from the surface to a depth of 10–60 cm of soil (depending on water content), providing observations within the root zone. Furthermore, applications are not limited to soil moisture. With measurements at multiple neutron energies, different heights above the ground or from directionally sensitive detectors [e.g., *Mascarenhas et al.*, 2009], snow, soil water content and biomass can potentially be determined independently from the soil moisture signal.

[8] One major advantage to the technique is the spatial scale of sample averaging. Subaerial (noninvasive) measurements of cosmic ray neutron fluxes in the 10^{-2} to 10^{2} eV energy range represent a sample area of tens of hectares for omnidirectional measurements at sea level. The sample area is large because neutrons travel tens to hundreds of meters in the atmosphere and instantly form a well-mixed reservoir of neutrons whose density is measured with a cosmic ray probe. The distance traveled in air is related to the large collision mean free path in air (~32 m) and the low energy loss per atmospheric collision (~7 collisions per log decrement of energy loss), both of which can be calculated from elementary nuclear properties [*Glasstone and Edlund*, 1952]. Furthermore, the tendency for neutrons to scatter diffusively contributes to the large footprint because diffusive radiation is governed by an inverse distance rather than an inverse square law [*Glasstone and Edlund*, 1952]. This increases the tendency for neutrons to mix in the atmosphere and limits the influence of local anomalies.

3. Cosmic Ray Neutrons Applied to Earth and Environmental Science

[9] We have demonstrated the viability of subaerial cosmic ray hydrometeorology through long-term monitoring of neutron intensity at sites in southeastern Arizona [*Zreda et al.*, 2008]. Our new results indicate that cosmic ray neutron intensity provides a robust proxy for the soil water or snowpack state (Figure 2). Soil wetting events are inferred from rapid drops in cosmic ray neutron intensity. In the summer, these drops correspond closely to rain events recorded at a tipping bucket gauges less than 1 km from the neutron detectors. As expected, following rain events the neutron intensity gradually recovers as drainage and evapotranspiration desiccate the upper 1 m of soil. Preliminary calculations suggest that time-lapse measurements can be used to infer additional parameters and states, such as the effective soil water retention parameters over the footprint, hydraulic conductivity or evapotranspiration rates.

[10] In winter, rapid drops in neutron intensity at the Mt. Lemmon, Arizona, site are usually caused by snowfall. Although we do not have precipitation data for snow events, surveys of snow water equivalent depth (SWE) were taken

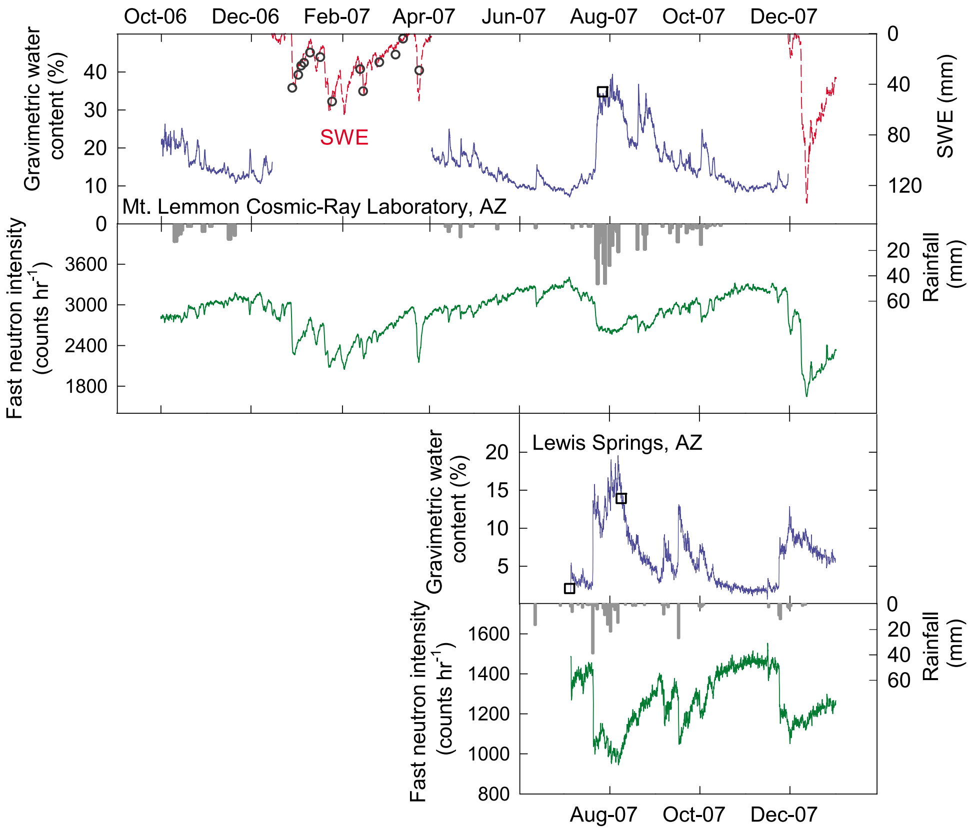

Figure 2. Neutron counting rates, rainfall, neutron-derived soil water content, and SWE values at the Mt. Lemmon Cosmic Ray Laboratory, Arizona (2745 m asl), and Lewis Springs, Arizona (1233 m asl). Circles and squares represent averaged values from snow coring and soil moisture surveys, respectively.

throughout the 2006–2007 snow season. Cosmic ray measurements of SWE correspond closely to data collected independently with a snow coring apparatus (Figure 2).

[11] Although neutron intensity is the primary data analyzed, the neutron energy spectrum contains additional information about the state and distribution of water at the land surface. For example, simultaneous measurement of thermal and epithermal or fast neutrons can be used to distinguish snow events from rain events, as we have done at the Mt. Lemmon Cosmic Ray Laboratory (Figure 3). Methods are summarized in Appendix A. Snow events there are characterized by a rapid increase in thermal neutron intensity with the first 1–3 cm of SWE, followed by a rapid decrease. This stands in contrast to the behavior of epithermal neutron intensity, which decreases monotonically with an increase in SWE or soil water content. Modeling and recent measurements suggests that thermal intensity should also increase during the wetting of initially dry (~0.03 cm^3 cm^{-3}) soils. When snow is absent, this nonmonotonic behavior provides a first-order means of calibrating and validating soil moisture data, since it is diagnostic of relatively dry soils.

[12] Whereas thermal and epithermal fluxes respond differently to land surface water, their responses to changes in cosmic ray "source" neutron intensity are identical. This means that the thermal/epithermal ratio is a function of soil water content and snowpack, but does not need to be corrected for variations in solar activity, barometric pressure, and location. However, the thermal/epithermal ratio will depend on soil chemistry because of the presence of neutron absorbing elements, such as B, Cl, K and Gd, which affect thermal neutrons, but not epithermal or fast neutrons. This means that the shape of a thermal/epithermal ratio versus soil moisture curve could be site dependent, whereas the shape of the epithermal neutron flux versus soil moisture curve should be nearly invariant.

[13] The neutron energy spectrum may also contain information about the spatial pattern of land surface water. In Figure 4, changes in the distribution of snow cover are manifested as a hysteretic loop comprising distinct accumulation and melting curves. We conjecture that the displacement between the curves is a consequence of nearly uniform snow accumulation, but highly nonuniform melting on slopes with different aspects. This effect is profound at the Mt. Lemmon Cosmic Ray Laboratory, which sits on an east-west trending ridge with a forested north face that tends to retain snow for much longer than the wildfire-ravaged south face.

[14] The sensitivity of neutron fluxes to aboveground water suggests it is possible to measure forest biomass over an area commensurate with the cosmic ray footprint. Neutron intensity should respond to both the hydrogen contained in plant water and carbohydrates, and to a lesser degree to plant carbon, which is also a neutron moderator. Because neutrons are more penetrating in canopies than microwave signals, the cosmic ray method should be better

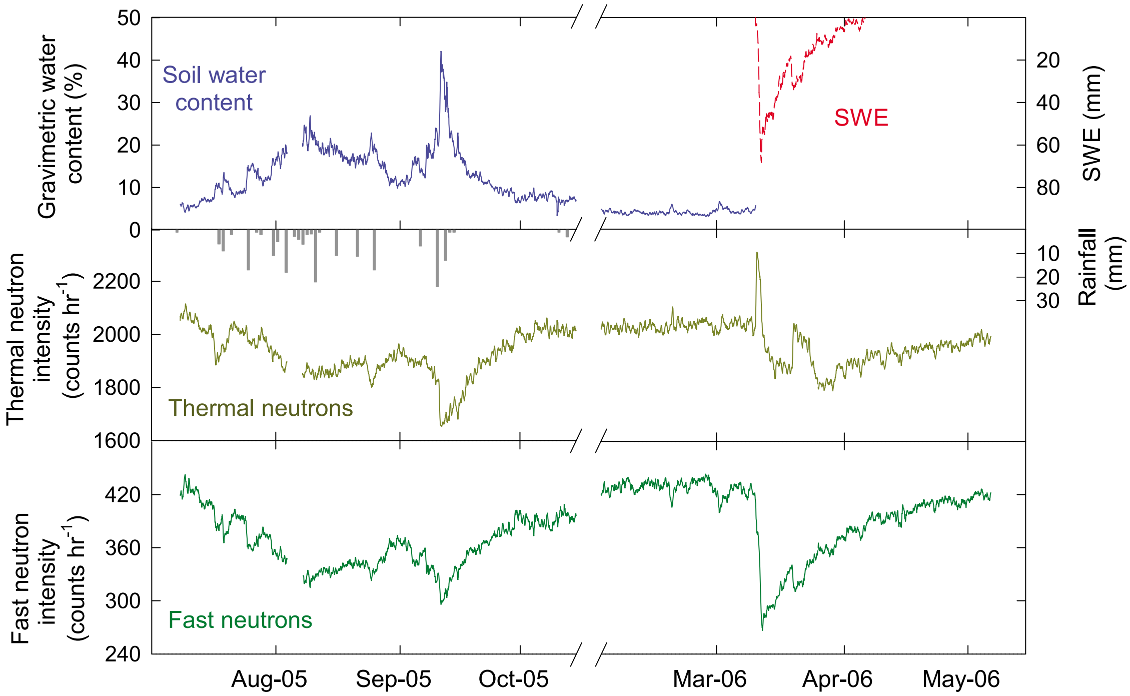

Figure 3. Response in thermal and epithermal energy bands to precipitation events. The first snow storm in March 2006 caused the thermal neutron counting rate to increase sharply while the epithermal counting rate decreased throughout the event. Spikes in the counting rate are absent during the preceding rain events, suggesting that the phenomenon is caused only by snow.

for examining dense biomes. Large amounts of neutron-moderating hydrogen and carbon residing in forests can have a substantial impact on neutron fluxes, particularly in rain forests where aboveground dry biomass can exceed 300 Mg ha^{-1} [*Saatchi et al.*, 2007]. Neutron transport simulations indicate that the presence of a mature tropical rain forest such as this can reduce the above-canopy fast neutron intensity by as much as 40% compared to unvegetated terrain. In such an extreme case the sensitivity at ground level to changes in soil moisture is reduced by 20%, suggesting that for thickly vegetated terrain additional field calibration points or calculated correction factors based on estimated biomass may be needed. However, simultaneous determinations of both soil water content and biomass may be possible with neutron measurements alone using spectral and/or directional neutron flux data or by positioning detectors above and below the canopy. It should be feasible to conduct real-time biomass surveys, from either below a forest canopy in ground based surveys, or from above a canopy using observation towers or low-flying aircraft (within ~200 m of the canopy). Cosmic ray neutrons could be used to complement existing remote sensing techniques such as synthetic aperture radar by providing ground control points, or as an additional and independent source of airborne data that can be incorporated into data assimilation algorithms and land surface models.

[15] To complement observational networks such as COSMOS which provide temporal continuity, roving surveys of neutron intensity can provide spatial continuity for mapping soil moisture over large areas. We recently conducted one such survey (Appendix A, section A2) along an east–west transect across the island of Hawaii to demonstrate the operational viability of ground based, roving measurements. Hawaii's trade wind-dominated climate and pronounced topography make for an ideal test bed: windward slopes receive substantially more rainfall than leeward slopes, giving rise to a sharp but persistent gradient in soil moisture, vegetation and soil development. Our results

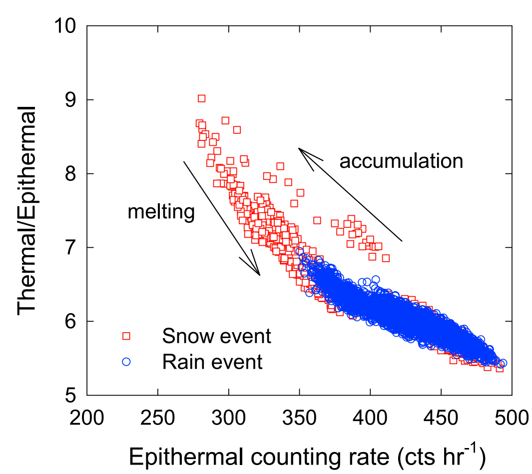

Figure 4. The evolution of the epithermal counting rate and thermal/epithermal ratio during rain and snow events recorded between July 2005 and May 2006. Epithermal neutrons (energy >0.5 eV) were recorded with a cadmium-shielded detector. The thermal neutron counting rate was calculated by subtracting the cadmium-shielded rate from the rate in an identical unshielded detector. Counting rates are corrected for solar activity variations using data from the Climax neutron monitor and for atmospheric pressure variations using hourly data collected on Mt. Lemmon.

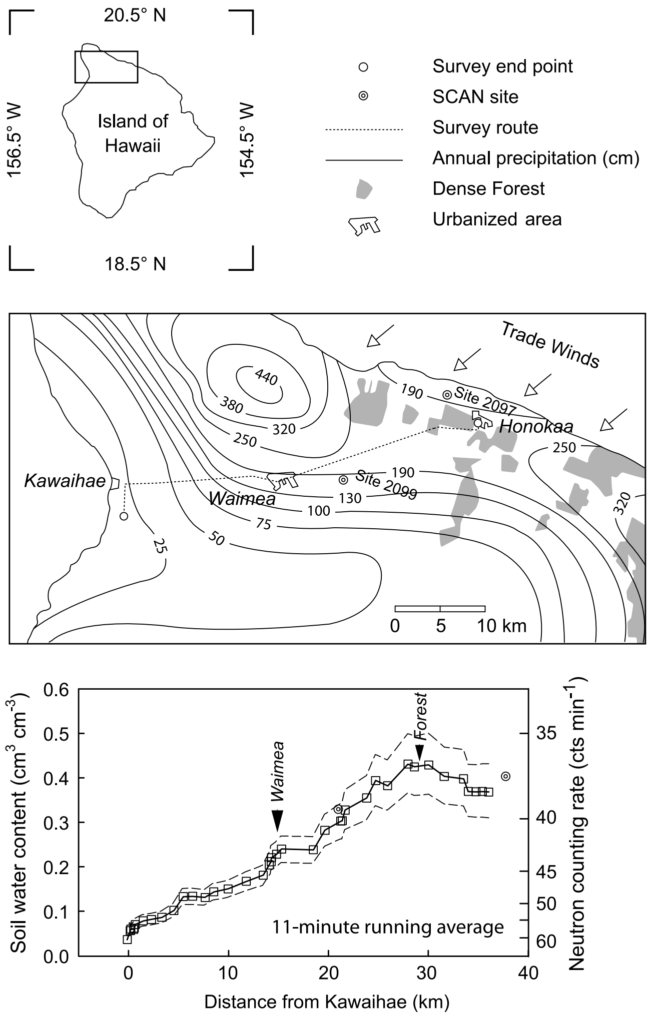

Figure 5. Roving soil moisture survey conducted on the island of Hawaii, 29 January 2010. Dashed lines represent 1σ uncertainty on the average neutron counting rate propagated to the soil water content. Independent moisture contents from the SCAN network are average values for Hydraprobe sensors at depths of 5–50 cm, as reported at http://www.wcc.nrcs.usda.gov/scan/. Annual rainfall isohyets are from *Armstrong and Bier* [1983].

(Figure 5), which show a marked decrease in soil moisture content toward the leeward coast, are qualitatively consistent with the observed nearly eightfold decrease in annual precipitation from windward Honokaa to leeward Kawaihae, and are quantitatively consistent with nearby point measurements from the Natural Resources Conservation Service's Soil Climate Analysis Network (NRCS SCAN). Coincidentally, the length of this transect, 37 km, is almost the same as the resolution of satellite moisture determinations, about 38 km for the passive mode of NASA's Soil Moisture Active/Passive Mission (SMAP) mission [*Spencer et al.*, 2009]. Our results suggest that ground truthing of a satellite pixel could be accomplished rapidly and without the intrinsic problems of point-scale averaging by using a single mobile array such as the one in this work.

[16] Applications of land surface neutron fluxes potentially extend to paleosoil moisture and snowpack determinations. Cosmogenic nuclides are produced in situ in the upper 1–2 m of the Earth's crust by cosmic rays and accumulate to measurable quantities over centuries or millennia [*Fabryka-Martin*, 1988; *Lal*, 1991]. Several nuclides are produced at low energy (below 10^7 eV), where neutron fluxes are most sensitive to the hydrogen content of surrounding materials. Production of these nuclides in situ in rock and soil should therefore be a function of soil moisture content and snowpack averaged over the exposure period of surface materials. The radionuclide ^{36}Cl produced from ^{35}Cl by the n, γ reaction [*Phillips et al.*, 2001] is particularly useful for this purpose because production occurs mainly below 10^1 eV, where neutron fluxes are particularly sensitive to soil water content and snow. Because primary cosmic ray intensity changes over time, mainly due to geomagnetic strength variations, measurement of an additional nuclide would be useful to normalize for changes in source intensity. In situ ^{10}Be is produced mainly at energies above 10^8 MeV, and so is far less sensitive to snow cover or soil water content. The ratio of ^{36}Cl/^{10}Be should therefore reflect integrated paleosoil moisture and snow conditions in the vicinity of stable (noneroding) surfaces.

4. Conclusions and Outlook

[17] The wealth of current and potential applications make the cosmic ray method appealing to scientists and engineers in many different fields, particularly those in which multihectare-scale measurements of soil moisture or snowpack are desired. With existing neutron detector technology it should be possible to monitor land surface water in previously problematic contexts, including saline environments, wetlands and peat bogs, rocky soils, the active layer of permafrost and water and snow intercepted by vegetation. Observations can be conducted at fixed sites, for example on eddy covariance towers, or from moving vehicles on public roads, from tractors in agricultural fields, from low-flying aircraft, and possibly even from instruments air dropped into remote areas. The remote sensing community can benefit from this technology by using cosmic ray probes to calibrate and validate sensors and data products without the problem of point-scale variability that besets most field moisture and snow measurements. Innovative detectors being developed for national security and nuclear nonproliferation applications, such as directionally sensitive neutron detectors [*Mascarenhas et al.*, 2009], promise to extend the cosmic ray method to a wider range of applications and spatial scales, and offer opportunities for fundamental research in support of the cosmic ray method.

Appendix A: Methods

A1. Stationary Measurements in Southeastern Arizona

[18] Measurements were obtained at the Mt. Lemmon Cosmic Ray Laboratory (32.4418 N, 110.7824 W) from October 2006 to January 2008 with neutron detectors placed 4 m above the ground on a tower inside the building. Neutrons were recorded with an array of ^{3}He-filled proportional counters having different energy sensitivities. Neutrons in the fast to epithermal range were recorded with a detector surrounded by 2.5 cm of low-density polyethylene and a 0.5 mm

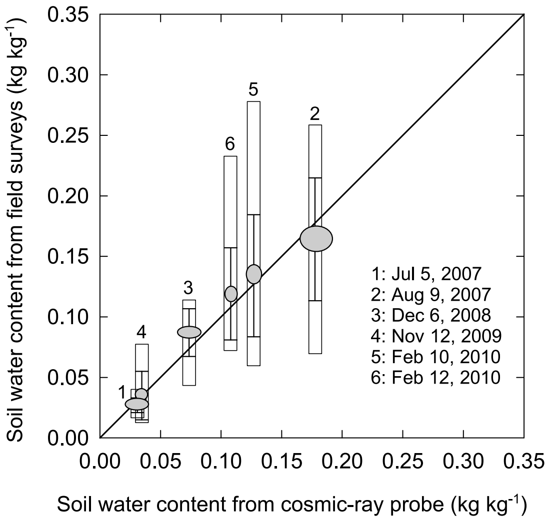

Figure A1. Water content at Lewis Springs, Arizona, determined from the cosmic ray probe using equation (A1) compared against averages of spatially distributed depth profiles collected in field surveys. Counting rates are corrected for variations in barometric pressure and solar activity. The vertical component of the error ellipse represents the standard error of the mean for depth-averaged samples taken in manual soil surveys. The horizontal component represents the standard error in the moisture determination propagated from the statistical uncertainty in the counting rate [*Zreda et al.*, 2008]. Error bars give the standard deviation of the depth-averaged samples, while the vertical rectangles encompass the entire range of depth-averaged samples.

thick outer layer of Cd shielding. Epithermal neutrons were recorded with two detectors covered by 0.5 mm of Cd shielding. Slow neutrons were recorded with an unshielded detector. We obtained a calibration curve for soil water content by fitting ground-level neutron fluxes simulated in MCNPX [*Pelowitz*, 2005] to the shape-defining function

$$\theta(N) = \frac{a_0}{\left(\frac{N}{N_0}\right) - a_1} - a_2 \tag{A1}$$

where θ is the volumetric or gravimetric water content, N is the neutron counting rate normalized to a reference atmospheric pressure [*Desilets et al.*, 2006] and solar activity level [*Kuwabara et al.*, 2006], N_0 is the counting rate over dry soil under the same reference conditions, and a_i are fitting parameters. The soil moisture dependence of near-surface neutron intensity on a per mass basis in the fast to epithermal energy range is given by $a_0 = 0.0808$, $a_1 = 0.372$ and $a_2 = 0.115$ for $\theta > 0.02$ kg kg^{-1}. These parameters were determined for a generic silica soil matrix. Excellent agreement (root-mean-square error <0.01 kg kg^{-1}) between water contents calculated with this equation and those measured gravimetrically in field samples at Lewis Springs, Arizona (Figure A1) suggest that modeled calibration parameters are widely applicable to soils derived from silicate rocks. Calibration samples were obtained at the Lewis Springs site (31.5615 N, 110.1404 W, WGS84) in five separate field campaigns from July 2007 to February 2010. We collected 48–72 soil samples from 16 to 24 locations within the footprint at three or four depths from 5 cm to 25 cm, and analyzed these samples for gravimetric water content using the oven-drying method. This calibration, normalized for the difference in altitudes using scaling factors [*Desilets et al.*, 2006], was then applied to the Mt. Lemmon site. Soil samples were collected on Mt. Lemmon using the same procedure as at the Lewis Springs site. In addition, in the winter of 2006–2007, snow water equivalent samples were collected with snow tubes at 8 radial locations 25 and 50 m from the laboratory.

A2. Roving Measurements in Hawaii

[19] Roving neutron measurements were conducted on 29 January 2010 with a detector array located in the cargo space of a rented sport utility vehicle. It took about 45 min, including stops at traffic lights, to complete the 37 km long transect. The detector array consisted of two ^{3}He-filled proportional counters moderated by 2.5 cm thick cylinders of low-density polyethylene, spaced 40 cm apart. Neutron intensity was integrated over 1 min intervals and barometric pressure was recorded at the end of each interval. Because elevations along the transect range from sea level to 850 m, it was particularly important to normalize neutron counting rates to the same barometric pressure. Neutron counting rates were reduced to sea level pressure (1013 mbar) using an exponential attenuation coefficient of 0.0067 mbar^{-1}, which was determined in a neutron monitor survey taken several days earlier.

[20] Data were collected while driving at highway speeds (up to 95 km hr^{-1}) along paved public highways between Honokaa and Kawaihae. Distance along the transect was determined by referencing pressure-based elevation measurements against elevations recorded a day earlier with the same instrument, and correcting for a small (<2 mbar) change in sea level pressure.

[21] Neutron counting rates were converted to soil moisture using equation (A1). The value of N_0 was determined from the computed ratio of neutron intensity over seawater to the intensity over dry soil. This ratio was calculated using the code MCNPX. The value of neutron intensity over seawater near the island of Hawaii was obtained from measurements conducted 2008 using the same detector tubes as in this survey.

[22] **Acknowledgments.** Work at the University of Arizona was supported by the COSMOS project (National Science Foundation grant AGS-0838491); NSF grants EAR-0126241, EAR-0636110, and EAR-0345440, Army Research Office grant 43857-EV; and the David and Lucile Packard Foundation (Fellowship for Science and Engineering 951832). Work at Sandia National Laboratories was supported by a Laboratory Directed Research and Development grant. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The Climax neutron monitor was supported by the National Science Foundation grant ATM-0339527 to the University of Chicago.

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