Cosmic-ray Soil Moisture Probe: A New Technology To Effectively Manage African Dryland Ecosystems

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Summary

An estimated 200 million rural smallholders practice livestock-based or mixed livestock-crop-based agriculture in sub-Saharan Africa, where levels of poverty and food insecurity are among the highest in the world. Demographic, environmental, and climate changes have led to diminishing supply of resources that is crippling dryland productivity and increasing people's vulnerability. There is a need for research to develop, monitor, and evaluate strategies to cope with diminishing resource availability and build resilient ecosystems. Reliable, long-term measurements of soil moisture are critically needed for addressing productivity and food security in African drylands. We propose that measurements of effective infiltration, plant available water, and deep drainage are sufficient metrics to understand dryland ecosystem health and to assess and evaluate restoration strategies. In this work, we evaluate the advantages and disadvantages of two different measurement methods, the cosmic-ray neutron method (as implemented in the COsmic-ray Soil Moisture Observing System (COSMOS)) and eddy covariance techniques, for long-term measurements of African dryland water balance. We compare estimates of ecosystem level daily evapotranspiration between the two methods over a six-month period at a site in central Kenya, and found the cosmic-ray method to be more appropriate. The eddy covariance data are smoother than the cosmic-ray measurements. But the cosmic-ray neutron probe method provides additional information on the key variable, area-average soil moisture, allowing us to partition rainwater into infiltration, runoff, evapotranspiration, and deep drainage. In addition, cosmic-ray neutron probes are easier to operate and maintain, more robust, and less expensive than eddy covariance towers, making them more appropriate for long-term deployments.

Introduction

Sixty percent of sub-Saharan Africa is pastoral or agropastoral land (Reynolds et al. 2007). These arid, semi-arid and subhumid regions are grassland to desert ecosystems and home to an estimated 200 million rural smallholders practicing livestock-based or mixed livestock-crop-based agriculture (Thornton et al. 2002; Robinson et al. 2011). These regions have some of the highest levels of poverty and food insecurity in the world (Thornton et al. 2002; Thomas and Twyman 2005), and they are exceptionally vulnerable to climate change. While projections of changes to mean annual precipitation vary from region to region, models agree that across all African drylands, rainfall will become less predictable, with shorter growing seasons (Thornton et al. 2006), and more frequent and more severe droughts (Sheffield and Wood 2008). This is the setting for one of Africa's greatest agricultural development challenges−dryland productivity and food security.

Of these pastoral/agropastoral areas approximately two thirds are drylands, where annual potential evapotranspiration exceeds rainfall by 200% or more, and traditional smallholder agriculture relies substantially or wholly on extensive livestock husbandry (Notenbaert et al. 2009). This resilient production system has evolved and persisted for millennia, and represents a highly adaptive relationship between human livelihoods and the environmental stresses that typify dryland environments. Tropical drylands experience not just low amounts of rainfall, but high rainfall variability both in space and time. Systems of mobile, flexible livestock herding over extensive ranges allow smallholders to buffer themselves against the variable environmental conditions at any single location, and to access key natural resources that are heterogeneously distributed across large spatial scales (Niamir-Fuller 1998). Smallholder livestock production in drylands is not an isolated socioeconomic system, but influences the national economies of all African nations with drylands. It is a critical source of protein, nutrition, and commerce for both rural and urban populations. For example, in Kenya, livestock contributed 50% to the national agricultural gross domestic production in 2004, and the proportional contribution continues to increase (Hesse and MacGregor 2006).

However the resource base for livestock production is shrinking due to four compounding effects:

(1) Population growth: there are more lives depending on each hectare (Notenbaert et al. 2009).

(2) Land conversion: usually to cropping, this leaves fewer hectares available (Herrero et al. 2009) and may increase dependence on ground water supplies to meet the increased evapotranspiration demand.

(3) Legacy of land degradation: today the same hectare produces less forage (Dregne 2002).

(4) Increasingly unpredictable climate: this results in fewer productive hectares per year, and is expected to reduce viable pastoral areas by 20% in 40 years (Falkenmark and Rockstrom 2008, Thornton et al. 2006).

It is the diminishing supply of resources for livestock-based agriculture that is crippling the system's productivity and increasing people's vulnerability (Thornton et al. 2006; Andersson et al. 2011). We need basic research to proactively develop, monitor, and evaluate strategies to cope with this 'diminishing resource syndrome' in drylands.

Mitigation of the diminishing resource syndrome has typically fallen into two strategies: a) do business as usual but search for more efficient and productive methods; or b) change to a new system. The first strategy falls in the sphere of range management. While managing livestock is an important issue, restoring the ecological functioning and productivity of the landscape is going to be an essential component to curtail the diminishing resource syndrome. However with increasing populations on limited lands, in many areas the demand for food is unlikely to be met by livestock management alone. The second strategy is one that many pastoralists all over Africa are now resorting to: trying to grow crops where traditionally they have only raised livestock. Depending on the context, this could increase vulnerability and food insecurity rather than reduce it. There is a need to understand these systems to find out where each of the two coping strategies or combination of the two strategies is most appropriate.

Dryland productivity is predominantly driven by landscape water balance, or the partitioning of incoming rainfall into different pathways in the ecosystem (runoff, groundwater recharge, evaporation, or transpiration). The more water that infiltrates the soil and is taken up by plants and transpired, the more plant productivity a landscape can yield. The more rainfall that is lost to runoff or evaporation directly from the soil, the smaller the proportion of soil moisture for plant growth. And importantly, the productivity of a landscape feeds back to affect the water balance in subsequent rainfall events (Ludwig et al. 2005). Thus as dryland vegetation degrades, the capacity of the landscape to capture and convert rainfall into productive growth also declines (Kefi et al. 2007).

Directly improving plant water use efficiency could be a target for enhancing productivity, but in landscapes where degradation has impaired water balance, the system is still inexorably dependent on ecohydrological constraints on the supply of water available to plants. Addressing this abiotic component of the system is necessary to reinstate water-soil-vegetation feedbacks, so the system can once again sustain productivity (King and Whisenant 2009). Increasing supply-side dynamics of water availability is the basis of the current "Blue Revolution" in agricultural research. Here water conservation practices deliver "more crop per drop", by enhancing water use efficiency, or the amount of productivity gained per unit of water consumed. The Food and Agriculture Organization of the United Nations promotes conservation agriculture with three principles: minimal soil disturbance, permanent soil cover, and crop rotations (http://www.fao.org/ag/ca/;

accessed on 1 August 2012). This approach has been shown to be successful in Tanzanian drylands (Owenya et al. 2012).

This concept can also be applied to rangelands. Instead of targeting water use efficiency at the scale of single crop plants or agricultural fields, the approach is aimed at the scale of land tracts of a perennial ecosystem (several hectares). However, at this scale additional complication is introduced, spatiotemporal heterogeneity of resources. Two hallmark traits of drylands are its patchy structure and the variable, pulse-like arrival of the key limiting resource, water. Their interactions hold the key to understanding and restoring ecosystem function (Ryan and Ludwig 2007; King et al. 2011).

Historically, the measurement of soil water dynamics at this field scale has been notoriously difficult given the inherent limitations of direct and indirect sampling methods (Robinson et al. 2008). An alternative measurement technique that uses eddy covariance towers (Stull 1988) provides information on the water, energy, and carbon balances of ecosystems, integrating over the tower's "footprint" area, with a diameter of approximately 10 times the tower height. For example, Fluxnet is a global network of more than 400 eddy covariance towers that have operated since the 1980's (Baldocchi et al. 2001), but with fewer than 20 stations in Africa, the continent is underrepresented. However, flux towers provide little or no information about plant available water at the footprint scale, thus limiting our ability to fully understand the soil-atmosphere coupling (Seneviratne et al. 2010) or partitioning of the water into their individual components.

The recent advent of the cosmic-ray neutron probe (Zreda et al. 2008) has opened the door for accurate measurements of near surface soil moisture at the landscape scale (Franz et al. 2012). Here, we propose to use the cosmic-ray moisture probe (Zreda et al. 2008) to derive key variables needed for monitoring of agropastoral systems. We first summarize the cosmic-ray neutron method (Zreda et al. 2008) as implemented in the COsmic-ray Soil Moisture Observing System (COSMOS) (Zreda et al. 2012). Then, we compare estimates of daily soil water flux derived from cosmic-ray neutron measurements with a collocated eddy covariance tower in a central Kenyan dryland. Finally, we identify some key points for consideration of the establishment of a cosmic-ray neutron probe monitoring network in African drylands to address the critical issues of productivity and food security.

Materials and Methods

Cosmic-ray Neutron Probe Method

The inverse relationship between soil moisture and the intensity of cosmic-ray fast neutrons above the surface has been known for several decades (Hendrick and Edge 1966). The removal of neutrons is dominated by neutron collisions with hydrogen atoms. Hydrogen has an extraordinarily high neutron stopping power, which is due to a combination of its high neutron scattering cross-section, high fractional energy loss per collision and low atomic mass (Zreda et al. 2008, 2012). Hydrogen's stopping power is an order of magnitude greater than any other element, making hydrogen the dominant factor in controlling neutron intensity (Zreda et al. 2012).

Using a moderated neutron detector placed above the surface (Figure 1), Zreda et al. (2008) found that differences in the relative count rate of fast neutrons (~10-100 eV) in air above land surface are related to the average amount of soil water present. Desilets et al. (2010) found the following calibration function between soil moisture, θ (m^3 m^{-3}), and fast neutron counts:

$$\theta(N) = \frac{0.0808}{(N/N_0) - 0.372} - 0.115 \qquad (1)$$

where N is the neutron counting rate normalized to a reference atmospheric pressure and solar activity level (Zreda et al. 2012), N_0 is the counting rate over dry soil under the same reference conditions, and the three coefficients were determined using a neutron particle transport code, MCNPx (Pelowitz 2005) for pure silica sand (SiO_2). The calibration parameter N_0 can be estimated at the probe site using volumetric soil moisture samples around the footprint (c.f. Dane and Topp

2002). Because the sensor gives an average neutron count over a circle with a radius of ~335 m (Zreda et al. 2008) and the sensitivity decreases with the distance from the probe, soil sampling at 18 locations (every 60^o and at radii of 25, 75, 200 m) gives a representative estimate of the mean water content over the footprint. Fast neutrons mix rapidly above the surface (velocities >10 km s^{-1} (Glasstone and Edlund, 1952)), indicating that horizontal soil moisture heterogeneity likely plays a minor role in the average footprint neutron count. In contrast to the horizontal footprint that is independent of soil moisture content, the vertical depth of measurement of the sensor does vary with soil water content ranging between ~10 cm and 70 cm for wet and dry conditions, respectively (Zreda et al. 2008). With a single or repeated calibrations at a site, Franz et al. (2012) found that sampling every 5 cm to a depth of 30 cm is adequate to accurately describe the average soil water content in the profile and thus estimate N_0 with an average RMSE of <0.02 m^{-3} m^3.

Figure 1. A cosmic-ray neutron probe (Model Number CRS 1000, Hydroinnova LLC, Albuquerque, NM, United States of America) installed at the Santa Rita Experimental Range site, located in Southern Arizona, United States of America.

COsmic-ray Soil Moisture Observing System

The COsmic-ray Soil Moisture Observing System (COSMOS) is a new national network in the continental United States of America designed for improving hydrometeorological forecasting (Zreda et al. 2012, data available at http://cosmos.hwr.arizona.edu/) by providing real-time estimates of soil moisture (Figure 2). Beginning in 2009, 50 cosmic-ray neutron probes were deployed to provide hourly estimates of soil moisture. The cosmic-ray neutron probes have been designed to be rugged, energy-efficient and independently powered using solar cells, and they are equipped with a satellite data modem for reliable transmission of data from any place on the globe. A data success rate of over 90% has been achieved from the COSMOS probes in the continental United States of America, and from affiliated probes in five other continents.

As part of the COSMOS project, all data are collected, processed, and checked for basic quality assurance and quality control in real-time, and then posted on the Internet. Currently, the measured neutron intensities are corrected for variations in geomagnetic latitude and local atmospheric pressure changes (Zreda et al. 2012). In the near feature, new corrections will be added to account for variations in lattice water, atmospheric water vapor and vegetation. Additional details about the cosmic-ray neutron probe method and the COSMOS project are in Zreda et al. (2012) and on line (http://cosmos.hwr.arizona.edu/).

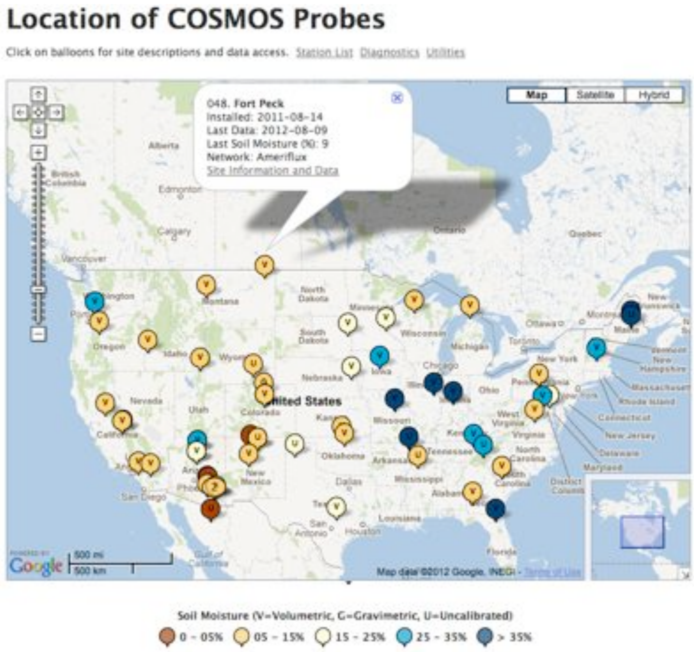

Figure 2. Location and status of COSMOS probes in the continental United States of America as of 9 August 2012 (http://cosmos.hwr.arizona.edu/Probes/probemap.php). Raw and processed data from individual sites are publicly available in real-time.

Instrumentation for Water Balance Measurements in Central Kenya

Beginning in September 2011, a cosmic-ray neutron probe was installed at a study site, referred to herein as Mpala North, in central Kenya, where a 20 m tall eddy covariance tower has been operating since 2009 (Caylor, unpublished data). The site is in the Upper Ewaso Ngiro River basin of the central Kenyan highlands (36°54'E, 0°20'N). It is characterized as semi-arid woodland or shrubland, receiving 450–500 mm yr^{-1} of rainfall, typically arriving in two rainy seasons, April–May and November–December (Franz et al. 2010). The vegetation has 10%–25% woody canopy cover, dominated by mixed Acacia species. The herbaceous layer has perennial and annual grasses, as well as a diversity of forbs and succulents, with 1–10 m bare patches with no perennial grass and sparse annual vegetation (Figure 3). Under current land use practices, average standing biomass is typically estimated to be 450–700 kg ha^{-1} (CNRIT 2011).

The site is located on the Mpala Research Centre Conservancy (MRCC), a 20 000 ha ranch that has been used for commercial cattle production for the last century, and since 1998 has been managed as a wildlife and research conservancy while maintaining a moderate cattle herd (1 tropical livestock unit (TLU)/10ha). Wildlife is abundant; elephant, giraffe, zebra, buffalo, impala, dik-dik, baboons, hyenas are common. The site is within 3 km of the Ewaso Ngiro River, which serves as the boundary between MRCC and communally-owned lands utilized and inhabited by Laikipia Maasai pastoralists. The communal areas have similar physiognomy and rainfall to the MRCC site, higher livestock stocking rates (1 TLU/3 ha), reduced wildlife densities, and decreased herbaceous vegetation cover (5%–50% less, varying with year and season; King, unpublished data). While land use is predominantly for livestock production, a limited number of community members began small-scale maize cropping along the river in 2011. In future work, the Mpala North site and adjacent community lands will be studied to compare landscape scale water balance and ecosystem function between the land use systems.

Figure 3. Vegetation composition and cover in central Kenya, January 2007.

Results

The daily time series of neutron-derived soil moisture, effective sensor depth, and rainfall from the study site (Figure 4) show the response of soil moisture to rain events. Using the time series of soil moisture data, we compute the daily flux of water into and out of the control volume (Figure 5). The positive values indicate infiltration of rainwater into the soil and negative values indicate losses of water to evapotranspiration (ET) and vertical leakage (L). Small positive anomalies in the dataset not correlated to rain events are due to uncertainty in either the neutron count statistics or rainfall record. To compare different measurement techniques, we look at the daily ET values derived from the cosmic-ray neutron probe and the daily average latent energy from the eddy covariance tower (Figure 6). Despite the differences in the measurement techniques and horizontal and vertical scales of measurements, the two time series agree reasonably well over the six-month study period. Because the cosmic-ray derived ET also contains L the values are higher than those derived from eddy covariance, which only estimate ET. Using additional information about the soil and vegetation, a soil water balance model can be used to separate the ET and L components from the integrated signal, for example using methods described in Rodriguez-Iturbe and Porporato (2004).

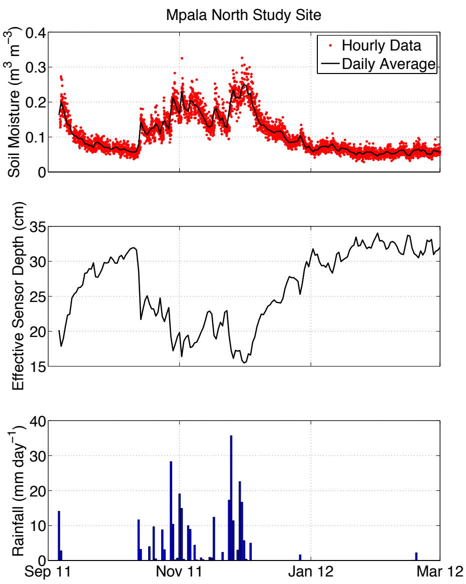

Figure 4. Daily soil moisture, effective sensor depth, and rainfall from the Mpala North study site in central Kenya.

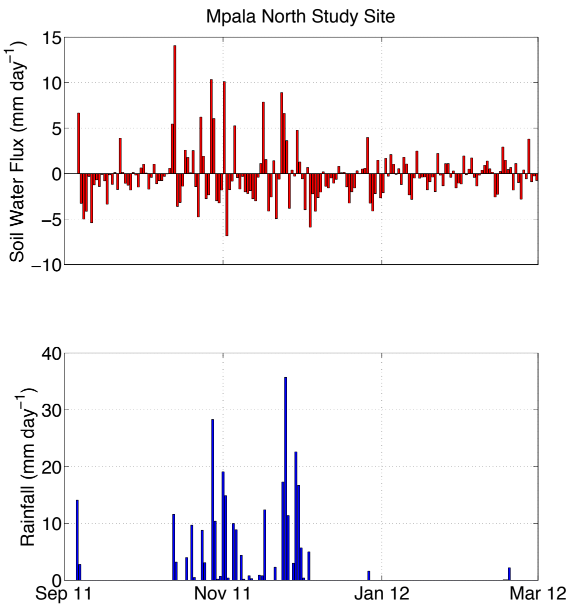

Figure 5. Estimates of daily soil water flux into and out of the control volume derived from the soil moisture time series.

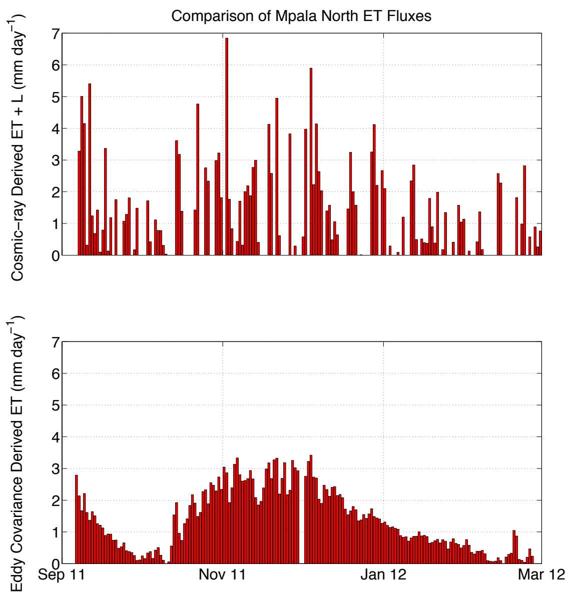

Figure 6. Comparison of landscape scale fluxes derived from the collocated cosmic-ray neutron probe and eddy covariance tower.

Discussion

Comparison of the daily water fluxes indicates a general agreement between the methods, but eddy covariance derived values are smoother than those derived from the cosmic-ray neutron measurements. Given the different information obtained from each instrument, the complimentary measurements from eddy covariance and cosmic-ray instruments are preferable to understand how these ecosystems function. However, limited research budgets and unfavorable site characteristics often restrict the total possible investment, and only one of the two instruments may be feasible. Three key differences between the measurement methods make the cosmic-ray neutron probes more suitable for monitoring and assessing the long-term ecosystem health and function of African drylands.

First, as we have described in the introduction, the key factor governing these dryland ecosystems is the partitioning of rainfall into runoff, infiltration, evapotranspiration, and deep drainage. Whereas the eddy covariance method provides measurements of the water, energy and carbon balances, they do not provide information on the soil water–the key variable. Knowing soil water is crucial because in order to estimate the various water fluxes in and out of the soil column, we need parameters and boundary conditions describing the physics of unsaturated water flow through porous media (Dingman 2002). Point sensors are often used to measure soil moisture, but their small support volumes (~10 cm^3) result in measurements that are not representative of the footprint scale (~1 km^2) because of small-scale heterogeneities within the footprint (Robinson, 2008). Thus, comparisons between land surface fluxes from eddy covariance towers and soil moisture dynamics based on point measurements may be difficult (Seneviratne et al. 2010). Because cosmic-ray neutrons provide area-average soil moisture (Zreda et al., 2012; Franz et al. 2012), we are able to derive effective (area-average) parameters controlling the flow of water through porous media and thus partition rainfall into infiltration, runoff, evapotranspiration, and deep drainage at the landscape scale. For rangelands, the amount of rainfall infiltrating into the soil is the key metric to find out how the ecosystem is functioning under different land uses or to evaluate effective restoration strategies (King et al. 2011). In addition, estimates of available water will be one critical piece to decide what vegetation is best suited to a particular ecosystem. Moreover, the water demand of various crops can be calculated for certain climates and compared to the estimate of available water in that ecosystem. In that regard, the amount of extra water needed from surface or ground water sources can be estimated, providing crucial information to stakeholders about the feasibility and environmental impact of the proposed land use change.

Second, from an operational and maintenance standpoint the cosmic-ray neutron probes are easier to install, calibrate, and less expensive to purchase and maintain than eddy covariance towers. The cosmic-ray sensor contains a gas-filled tube, high voltage power source, datalogger, 40 Ahr battery, 60 W solar panel, and satellite modem. This is simple when compared to the dozens of instruments required for an eddy covariance tower. In terms of maintenance, the major concerns are keeping the cosmic-ray probe battery charged and relative humidity inside the instrument box low. In terms of calibration, and as with most instruments, repeated calibrations are preferred and will ensure the highest quality of data, but a single calibration is adequate because of the long-term stability of the N_0 parameter (Franz et al. 2012). In contrast, eddy covariance towers require yearly calibrations of the individual instruments and a full time technician to maintain performance. Eddy covariance towers operate best with AC power but can be supported with several solar panels and battery banks. In terms of data, the cosmic-ray probe was designed to send a minimal amount data (ambient pressure, temperature, humidity, voltage, neutron count), or approximately 10 bytes of raw data, per transmission (usually every hour). Eddy covariance towers make measurements many times per second in order to quantify the departures from the mean and accurately estimate the half-hourly averages. In addition, eddy covariance data require a significant amount of post processing time and skilled personnel for high quality datasets (Stull 1988).

Third, the costs of the two instruments are different. Principal investment of eddy covariance tower equipment is approximately \$100 000 with additional costs for maintenance, data transfer, data processing, and skilled onsite personnel. In contrast, cosmic-ray neutron probes cost approximately \$20 000 and require substantially less maintenance, data transmission cost and processing, and do not require permanent personnel on site.

Conclusions

We propose that measurements of effective infiltration, plant available water, and deep drainage are sufficient metrics to understand ecosystem health and function in Africa drylands. This information is critical for stakeholders who wish to increase productivity and food security in their ecosystems. In addition, these data will provide useful landscape water metrics to assess and evaluate different land use and restoration strategies in drylands. Given the advantages and disadvantages of each measurement method described above, we find the cosmic-ray neutron method more appropriate than the eddy covariance technique for long-term environmental monitoring in African drylands. Most importantly, the cosmic-ray neutron probe method provides information on the area-average soil moisture–the key variable–allowing partitioning rainwater into infiltration, runoff, evapotranspiration, and deep drainage. Cosmic-ray neutron probes were designed to be robust, have low power consumption, low maintenance, and high data reliability making them superior for long-term deployment in remote ecosystems. We suggest that reliable long-term measurements of soil moisture constitute the critical information needed for addressing productivity and food security in African drylands.

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