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Monitoring water content dynamics of biological soil crusts

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ABSTRACT

Biological soil crusts (hereafter, “biocrusts”) dominate soil surfaces in nearly all dryland environments. To better understand the influence of water content on carbon (C) exchange, we assessed the ability of dual-probe heat-pulse (DPHP) sensors, installed vertically and angled, to measure changes in near-surface water content. Four DPHP sensors were installed in each of two research plots (eight sensors total) that differed by temperature treatment (control and heated). Responses were compared to horizontally installed water content measurements made with three frequency-domain reflectometry (FDR) sensors in each plot at 5-cm depth. The study was conducted near Moab, Utah, from April through September 2009. Results showed significant differences between sensor technologies: peak water content differences from the DPHP sensors were approximately three times higher than those from the FDR sensors; some of the differences can be explained by the targeted monitoring of biocrust material in the shorter DPHP sensor and by potential signal loss from horizontally installed FDR sensors, or by an oversampling of deeper soil. C-exchange estimates using the DPHP sensors showed a net C loss of 69 and 76 g C m^{-2} in control and heated plots, respectively. The study illustrates the potential for using the more sensitive data from shallow installations for estimating C exchange in biocrusts.

1. Introduction

Near-surface soil-water content exerts a significant influence on surface-energy fluxes and climate modeling (Schmugge, 1998; Vereecken et al., 2008) and, therefore, needs to be included when environmental processes are up- and downscaled. Pitman (2003) argued that land surface plays a central role in parameterizing climate models in which the energy budget is affected by partitioning of the near-surface water budget. In arid climates, the partitioning of near-surface water loss between plants and soil governs overall water flux into slower pathways (transpiration) and faster pathways (evaporation). In landscapes with sparse vegetation, higher water retention in surface soils promotes evaporation (Young et al., 2009), restricting water availability for shrubs. Krishnamurti and Biswas (2006) examined energy partitioning between latent and sensible heat fluxes during a monsoon season and showed that latent heat flux dominates the surface energy flux, caused by water exchange, at the onset of monsoonal storms. Douglas et al. (2009) showed that irrigation associated with agriculture and land-use change altered evapotranspiration rates and mesoscale precipitation. By extension, these changes in energy balance and precipitation patterns are affected by surface soil-water content (Belnap, 2006).

Biological soil crusts (biocrusts)—a soil-surface community of cyanobacteria, fungi, lichens, and mosses that live at the soil surface—affect most soil properties. All biocrust organisms readily absorb water; this absorption increases with biocrust biomass. Biomass increases with the developmental stage of the biocrusts, as well as with reductions in potential evapotranspiration (PET) (Belnap, 2006). These organisms also cause the formation of micro- and macropores, through both their movement and growth, increasing soil porosity. However, biocrust organisms, by their very presence on the soil surface and swelling upon wetting, can also clog soil pores, reducing soil porosity (Eldridge, 2003). This reduction in soil porosity is especially noticeable with the presence of lichens and mosses, because they actually cover the soil surface; in comparison, microbial cyanobacteria and fungi weave throughout the soil and are therefore less likely to clog pores. In climates where soils freeze, biocrusts roughen the soil surface and enhance infiltration, whereas in hot deserts, cyanobacteria can

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smooth the surface, reducing infiltration.

Biocrusts also contribute newly fixed C and nitrogen (N) to underlying soil; soil moisture plays a critical role in both the release and uptake of these (Belnap et al., 2005). For example, many previous laboratory studies have shown that maximal photosynthetic rates occur at moderate water content; saturation or drying out resulted in lower rates (e.g., Brostoff et al., 2005; Lange et al., 1998). N fixation also varies with moisture content (Belnap, 2003). Past measurements of water content effects on biocrust C and N fixation have focused on measurements of thallus water content expressed as precipitation equivalent (e.g., Lange et al., 1998; Lange, 2002) or on a gravimetric basis (Lange et al., 2006). These destructive measurements are typically part of laboratory experiments; but, although destructive sampling can be used to obtain direct measurements of near-surface water content, this method is not conducive to capturing transient natural drydowns following precipitation events. Thus, the challenge to date has been in identifying nondestructive field-measurement methods that can capture the dynamic behavior of water exchange in the upper few millimeters to centimeters of the soil profile, where biocrusts dominate.

Automated, nondestructive water content measurement systems, which provide the benefits of high-temporal-resolution data collection, have over the past two decades become commercially available and very effective. In many cases, the technology relies on the measurement of electromagnetic properties of the soil or materials being sampled, and generally falls into categories of time-domain reflectometry (TDR) and frequency-domain reflectometry (FDR). Sensors are generally available with lengths varying from 5 to 30 cm, and with a sampling volume that depends on waveguide length and spacing (i.e., longer waveguides and wider spacing increases the sampling volume [Ferre et al., 1998]). Because of the sensor length and the sampling volume, and depending on the orientation of the sensors (vertical versus horizontal), these sensors may not be sensitive enough to measure near-surface soil water content or to detect small (<2 mm) rainfall events. Recently, Weber et al. (2016) reported results for a biocrust wetness probe (BWP) that produced reliable soil water content measurements for the upper 5 mm, with predominantly linear relationships between measured electrical conductivity and water content.

Additional methods of measuring water content are based on nuclear or ground-penetrating radar responses, but these also have drawbacks. For example, neutron-moderation measurement has a radius of influence that is water content dependent, with a reported radius range from 25 to 100 cm in quartz sand for water content ranging from 0.0 to 0.5 $cm^3\ cm^{-3}$, respectively (Greacen et al., 1981). Measuring the water content of surface material will clearly be influenced by the loss of fast neutrons into the atmosphere. Ground-penetrating radar (GPR) is capable of estimating near-surface soil water content (Huisman et al., 2003); however, surface roughness negatively affects the ability of many GPR antenna assemblies, including off-ground GPR methods, to measure near-surface materials consistently (Lambot et al., 2006; Weihermuller et al., 2007). Direct placement of the antenna on top of biocrusts can damage the brittle crust surface, and orienting the GPR source above ground surface can lead to distortion of electromagnetic waves and measurement error (Rappaport, 2007). Both the neutron probe and GPR are generally not automated and require human intervention.

The use of soil thermal response from heat-pulse sensors is a technology that appears to provide reliable water content values, even in near-surface conditions. These heat-pulse sensors have been used successfully in field situations (Bremer, 2003; Campbell et al., 2002; Heitman et al., 2003; Young et al., 2008) and more recently in very-near-surface soils as a means of estimating sensible heat flux and, hence, soil-water evaporation (Deol et al., 2012; Heitman et al., 2008; Xiao et al., 2011). Ren et al. (2005) compared short TDR sensors with dual-probe heat-pulse (DPHP) sensors (both 4 cm long). They found that both technologies yielded reliable results but that errors in water content measured using the DPHP method were lower than when using the TDR sensors. For the field situation reported in the current study, depth of interrogation was even shallower than that considered in the Ren et al. (2005) study; use of the DPHP method could, therefore, become the better choice.

What is unique about this study is the measurement of thermal properties as a means of estimating biocrust water content in very-near-surface environments, and the side-by-side testing of DPHP and FDR sensors installed in the field and monitored for a spring and summer season. If the DPHP method proves reliable, the water content results can then be used to estimate activity times of biocrusts and thus their contribution to ecosystem processes such as C fluxes (through photosynthesis and dark respiration). The overall objectives of this research were to (1) test and compare responses from DPHP sensors (installed vertically) and FDR sensors (installed horizontally) used to measure near-surface water content of intact biocrusts, and (2) use those measurements—along with previously measured relationships on the same biocrusts between temperature, water content, net photosynthesis, and dark respiration—to estimate C exchange for a 160-d period.

2. Materials and methods

2.1. Location

Water content measurements were collected at an existing U.S. Geological Survey (USGS) research site northeast of Moab, Utah, near Castle Valley (38.674480° N latitude, 109.414918° W longitude, 1420-m elevation). The field site lies on a cuesta, or pediment, containing soil that was reported by Johnson et al. (2012) as a Lithic Torriorthent—a relatively undeveloped, fine, sandy loam ranging in depth from 10 to 15 cm. The soils within this complex are well drained, and the range in mean annual precipitation is between 152 and 356 mm. The soil surface is covered with an undisturbed, pinnacled biocrust whose photosynthetic components are dominated by cyanobacteria (predominantly *Microcoleus vaginatus*), lichen (*Collema tenax* and *Collema coccophorum*), and moss (*Syntrichia caninervis*) (Belnap, 2003; Darrouzet-Nardi et al., 2015).

2.2. Experimental setup

The field site had been previously instrumented for treatments of supplemental heat using infrared (IR) lamps. Heat-treated plots were warmed using a lamp (model MRM-1208; 120 V, 800 W 6.7 A, 35 in) with a modified reflector (Kalglo Electronics Co., Inc, Bethlehem, Pa., USA) to achieve surface-soil temperatures averaging 2 °C above ambient temperatures through each day and night (Johnson et al., 2012). For this research, only two plots were used: a control plot (labeled at the site as “C-2 IR lamp control” having a lamp hood but no heating element, hereafter called *control plot*) and a heated plot (labeled at the site as “C-4 IR lamp,” hereafter called *heated plot*).

Dual-probe heat-pulse measurements were made using sensors manufactured by East 30 Sensors, Inc. (Pullman, Wash., USA). Sensors consisted of two needles, each 30 mm long and 0.9 mm in diameter, with a nominal spacing of 6 mm. One needle contained a 40-Ω heating wire (Evanohm, Wilbur B. Driver Co., Newark, N.J.), and the other needle contained a thermistor (halfway down the needle) to measure temperature. Sensor leads were encased in small-diameter plastic insulating tubing. Data were collected using a datalogger (model 23X, Campbell Scientific, Inc., Logan, Utah)