Monitoring water content dynamics of biological soil crusts

M.H. Young^{1*}, L. Fenstermaker², J. Belnap³

1 – Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas
at Austin, Austin, TX

2 – Division of Earth and Ecosystem Sciences, Desert Research Institute, Las Vegas, NV

3 – U.S. Geological Survey, Southwest Biological Science Center, Moab, UT

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* corresponding author. Current address: University Station, Box X, Austin, TX 78713-
8924; +001-512-475-8830; michael.young@beg.utexas.edu

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.

Keywords: soil water content; biological soil crusts; monitoring; dual-probe heat pulse

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,

1 by their very presence on the soil surface and swelling upon wetting, can also clog soil pores,
2 reducing soil porosity (Eldridge, 2003). This reduction in soil porosity is especially noticeable
3 with the presence of lichens and mosses, because they actually cover the soil surface; in
4 comparison, microbial cyanobacteria and fungi weave throughout the soil and are therefore less
5 likely to clog pores. In climates where soils freeze, biocrusts roughen the soil surface and
6 enhance infiltration, whereas in hot deserts, cyanobacteria can smooth the surface, reducing
7 infiltration.

8 Biocrusts also contribute newly fixed C and nitrogen (N) to underlying soil; soil moisture
9 plays a critical role in both the release and uptake of these (Belnap et al., 2005). For example,
10 many previous laboratory studies have shown that maximal photosynthetic rates occur at
11 moderate water content; saturation or drying out resulted in lower rates (e.g., Brostoff et al.,
12 2005; Lange et al., 1998). N fixation also varies with moisture content (Belnap, 2003). Past
13 measurements of water content effects on biocrust C and N fixation have focused on
14 measurements of thallus water content expressed as precipitation equivalent (e.g., Lange et al.,
15 1998; Lange, 2002) or on a gravimetric basis (Lange et al., 2006). These destructive
16 measurements are typically part of laboratory experiments; but, although destructive sampling
17 can be used to obtain direct measurements of near-surface water content, this method is not
18 conducive to capturing transient natural drydowns following precipitation events. Thus, the
19 challenge to date has been in identifying nondestructive field-measurement methods that can
20 capture the dynamic behavior of water exchange in the upper few millimeters to centimeters of
21 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 $0.5 \text{ cm}^3 \text{ cm}^{-3}$, 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

1 methods, to measure near-surface materials consistently (Lambot et al., 2006; Weihermuller et
2 al., 2007). Direct placement of the antenna on top of biocrusts can damage the brittle crust
3 surface, and orienting the GPR source above ground surface can lead to distortion of
4 electromagnetic waves and measurement error (Rappaport, 2007). Both the neutron probe and
5 GPR are generally not automated and require human intervention.

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

17 What is unique about this study is the measurement of thermal properties as a means of
18 estimating biocrust water content in very-near-surface environments, and the side-by-side testing
19 of DPHP and FDR sensors installed in the field and monitored for a spring and summer season.
20 If the DPHP method proves reliable, the water content results can then be used to estimate
21 activity times of biocrusts and thus their contribution to ecosystem processes such as C fluxes
22 (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, 1,420-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; 120V,

800W 6.7A, 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 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-ohm 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) powered by a deep-cycle marine battery and a trickle charger. Additional information on data collection using these sensors was described by Bristow et al. (1994), Ochsner et al. (2003), and Young et al. (2008). Measurements were taken at 4-hr intervals, beginning 10 April 2009 and continuing through 16 September 2009, or about 5.5 months. Logger problems during short periods led to some data loss, totaling 33 d across 10 gaps. We note that the depth of installation of the thermistor (10.6–15 mm) is below that expected to cause error in thermal-property estimates, which can become an issue in shallow-soil monitoring (Xiao et al., 2015).

A total of eight DPHP sensors were used in this study, four sensors in each of two plots. Biocrust material into which the sensors were installed (Fig. 1) varied by plot. Sensors in the

control plot were installed in soil that was populated in a progression from cyanobacteria-dominated (*Microcoleus vaginatus*) (sensor 1-1) to moss-dominated (*Syntrichia caninervis*) (sensor 1-4). In the heated plot, surfaces were represented mostly by soil material (sensor 2-5), progressing into a mix of cyanobacteria and moss (sensor 2-8). All sensors were installed with needles vertically downward for the first 40 d (DOY 100-140), after which four sensors (1-3, 1-4, 2-7, and 2-8) were reoriented at a 45° angle for the remainder of the study (i.e., DOY 140-260). The condition of the biocrusts, in terms of increased growth or loss of biomass, was assumed constant during this relatively short experimental period.

As indicated earlier, thermal measurements were meant to augment the ongoing monitoring program initiated by the USGS. Part of that monitoring program included water content reflectometers (model CS-616, Campbell Scientific, Inc., Logan, Utah), which were installed in both plots considered here. Six sensors (three per plot) were installed horizontally 5 cm below ground surface (Fig. 1) and connected to a different logger system (model CR-10x, Campbell Scientific, Inc., Logan, Utah), which was powered using available line power. Data were collected hourly during the same monitoring period as that of the DPHP sensors.

2.3 Experimental Data Analysis

Analysis of DPHP data was fully described by Young et al. (2008). Briefly, temperature changes at a distance, r , from a heating needle energized for an 8-sec heating period were estimated using the analytical solution to the heat-flow equation for a short-duration heat pulse through an infinite line source (de Vries, 1952; Kluitenberg et al., 1993; Mori et al., 2003):

$$\Delta T(r, t) = \frac{q'}{4\pi C \kappa} \left[Ei \left(\frac{-r^2}{4\kappa(t-t_o)} \right) - Ei \left(\frac{-r^2}{4\kappa t} \right) + st \right] \quad (1)$$

where T is temperature ($^{\circ}\text{C}$); t is time from beginning of heating; t_o is time after heating ceases; q' is the quantity of heat liberated per unit length of heater per unit time (J m^{-1}); C is the volumetric heat capacity ($\text{J m}^{-3} ^{\circ}\text{C}$); κ is the thermal diffusivity ($\text{m}^2 \text{s}^{-1}$), which is the quotient of the λ/C , where λ is the thermal conductivity ($\text{J m}^{-1} \text{s}^{-1} ^{\circ}\text{C}^{-1}$); Ei is the exponential integral; and s is ambient temperature drift. In this approach, we used a Levenberg-Marquardt (LM) parameter-optimization scheme that uses as independent variables soil-water content (shown in equation 10 in Young et al., 2008), apparent DPHP needle spacing, r , and temperature drift, s . The approach taken here differs slightly from that reported by Zhang et al. (2014) in addressing ambient temperature drift, which can be significant in near-surface desert environments.

To address our objectives, peak water content differences were calculated as a measure of response from precipitation. Peak water content differences were determined by subtracting initial water content obtained before the precipitation event occurred from the highest measured water content during/after the event. Relative differences in drydown behavior were also evaluated for up to 72 hr after these precipitation events. Drydown rate is important because photosynthetic activity is enhanced for some time after precipitation ends; differences in water content measurements could influence C exchange, especially after water content reduces to a level below 20%, when biological activity ceases in significance (Fig. 2). Here, the rate of change of water content (i.e., slope as a function of time) was calculated for DPHP sensors only in control and heated plots, using the time at, and quantity of, peak water content as the starting

point and then extending measurements forward until a substantial decrease in slope was observed. Slope was expressed as total change in water content (from the maximum recorded value) per 4-hr increment of time.

To illustrate the importance of near-surface soil water content measurements, data from Grote et al. (2010) were used to estimate C dynamics during the 160-d period of our field study. Grote et al. (2010) collected samples from the same field site and, in the laboratory, measured C flux (in $\mu\text{mol m}^{-2} \text{s}^{-1}$) at progressively higher temperatures and higher water content. Their data (Table 3, p. 2769) for net photosynthesis and dark respiration were fitted to a polynomial approximating a paraboloid:

$$C = a + bT + c\Theta + dT^2 + e\Theta^2 \quad (2)$$

where C is C flux ($\mu\text{mol m}^{-2} \text{s}^{-1}$), T is soil temperature ($^{\circ}\text{C}$), and Θ is soil-water content expressed as percent saturation. The data used to fit equation (2) were augmented to include zero net photosynthesis and dark respiration for percent saturations below 20% (as observed by Lange et al., 1994) and then used to fit surfaces (Fig. 2). Data collected using DPHP and FDR sensors were then used in combination with soil temperature collected hourly in each plot to calculate net photosynthesis during daylight hours and dark respiration between sunset and sunrise. Results are expressed as positive numbers when the biocrusts gained mass and negative numbers when they lost C to the atmosphere (both in units of g C m^{-2}).

2.4 Statistical Analysis

To better understand sensor responses from precipitation events—which were further subdivided into treatment (control versus heated), DPHP sensor orientation (vertical versus slanted at a 45°

angle), and sensor type (DPHP [thermal] versus FDR [electromagnetic])—statistical tests were conducted to help define subsequent binning and presentation of results. First, a standard t-test determined whether DPHP sensor orientation (vertical versus slant) affected mean peak water-content differences, regardless of plot treatment. A nonparametric t-test (Mann–Whitney rank-sum test) was used to assess whether plot treatment (control versus heated) influenced water content differences while grouping together sensor orientation, and whether mean peak water content differences from the DPHP sensors differed from those of the FDR sensors. (Data were not normally distributed, so standard t-tests were not used.) All comparisons were conducted using SigmaPlot (version 13.0), with $\alpha = 0.05$ and $p < 0.01$ indicating significance, unless otherwise noted.

3. RESULTS

During the 160-d period, 32 discrete precipitation events were recorded, with depths ranging from 0.1 to 12.1 mm and a total recorded depth of 89.4 mm. Among these, 10 events coincided with satisfactory water content data collection and analysis using both DPHP and FDR systems, ranging in depth from 0.7 to 12.1 mm (Table 1). The average response of all eight DPHP and six FDR sensors (Fig. 3) are plotted against each other and the precipitation events (shown as stars). In some cases (e.g., DOY 177), total precipitation depth is spread across several hours, whereas in other cases (DOY 258), the bulk of the precipitation occurred in a single high-intensity event. In general, results show consistently higher peak water content in DPHP versus FDR sensors, a higher drydown rate after peak water content, and higher baseline water content during long periods between precipitation events.

1 The standard t-test used to assess mean peak water content differences using DPHP sensors
2 (0.153 versus 0.127 cm³ cm⁻³ for vertical versus slanted orientation, respectively) showed that
3 differences were not statistically significant ($p = 0.555$), although vertical sensors did record
4 larger peak water content differences. With sensor orientation not considered a significant factor,
5 median peak water content differences from the DPHP sensors in the control versus heated plots
6 (0.129 versus 0.145 cm³ cm⁻³) were also assessed and found not statistically significant
7 ($p = 0.756$). Likewise, mean peak water content differences for the FDR sensors in the control
8 and heated plots (0.034 versus 0.045 cm³ cm⁻³) were not statistically significant ($p = 0.342$).

9 With plot treatment also not considered a significant factor, peak water content differences
10 for all DPHP sensors were binned into a single population, as were FDR measurements. Median
11 peak water content results (DPHP = 0.139 and FDR = 0.038 cm³ cm⁻³) were significantly
12 different ($p = 0.006$). Differences in DPHP versus FDR measurements can also be seen when
13 peak water content differences are compared graphically (Fig. 4). DPHP sensors, given the
14 installation method, clearly recorded larger increases in water content than did the FDR sensors,
15 as seen by the low slope value (slope = 0.23) in the regression line. The effect of different
16 measurement intervals on peak water content differences was not considered.

17 Carbon dynamics as a function of time (Fig. 5a) show a net loss of C from the biocrusts to
18 the atmosphere of 69 and 76 g C m⁻² in control and heated plots, respectively. Three distinct
19 periods of C dynamics with time are noted (and described below), from DOY100-125, DOY125-
20 180, and DOY180-260. Focusing on the first 10 d or so (Fig. 5b) during period I, both control
21 and heated plots track closely on top of one another, with <1 g m⁻² difference. But net C
22 exchange in the two plots then deviates as flux remains approximately unchanged in the control

plot (slope of C mass = $-0.010 \text{ g C m}^{-2} \text{ d}^{-1}$) and substantially negative in the heated plot (slope = $-0.133 \text{ g C m}^{-2} \text{ d}^{-1}$), indicating loss of C to the atmosphere.

As time progresses into period II (DOY125-180) (Fig. 5a), C loss to the atmosphere accelerates in both control and heated plots (slopes = -0.323 and $-0.395 \text{ g C m}^{-2} \text{ d}^{-1}$), but the steeper slope in the heated plot potentially shows the effect of the heating element. During period II, the root-mean-squared deviation in temperature between control and heated plots was 5.31°C ; temperature in the heated plot was higher than in the control plot in 75.1% of the hourly measurements. During period III (DOY180-260), net C exchange to the atmosphere in control and heated plots was nearly identical (slopes = -0.646 and $-0.660 \text{ g C m}^{-2} \text{ d}^{-1}$), reflecting the relatively low influence of supplemental heating and the higher influence of low water saturations at the end of the summer.

Calculations of C dynamics using FDR in this case were hampered significantly by the nearly constant estimates of saturation below 20%, when biological activities tend rapidly toward zero. For example, only 50 and 244 readings (out of $\sim 3,800$) in control and heated plots, respectively, were $> 20\%$ saturation; the large data gaps when C exchange could not be estimated rendered comparisons of C dynamics with the DPHP sensors unusable. The horizontal orientation of the FDR sensor beneath the biocrusts and the dominance of the low-precipitation depths in this semi-arid site led to an oversampling of deeper soil at the expense of monitoring biocrust material.

4. DISCUSSION

Moisture sensor comparison: Whereas previous efforts have used various techniques to measure soil moisture in the near-surface environment, none have used the thermal-sensor technologies

1 reported here. We found that DPHP sensors provided the most realistic measure for soil moisture
2 relevant to biocrusts activity, and better expressed the variability in water content values
3 expected after precipitation and drydown events. The differences in sensitivity between the
4 technologies are mostly the result of differences in sampling volume, which is a function of the
5 waveguide spacing and diameter, and of the length of the sensor. For example, Vaz et al. (2013)
6 reported on sampling diameters for a number of sensor technologies, including the CS-616, a
7 model similar to the CS-615 used in our study. Their results showed a sampling diameter equal
8 to 12.2 cm. A sensor installed parallel to ground surface at 5 cm depth could therefore result in
9 some signal loss at ground surface, and in the sampling of soil below the sensor to a depth of
10 ~11 cm, well below the soil of interest. Moreover, Logsdon (2008) showed in both laboratory
11 and field settings that the CS-616 sensor installed in soils with wet and dry regions—as expected
12 in the field environment reported here—preferentially responds with a higher dielectric constant
13 and hence higher water content, creating a distorted cylinder (transverse) surrounding the sensor.

14 DPHP sensors, however, sample the biocrusts from the upper surface downward into the
15 biological mat itself, focusing the sampling on the more important depth where the organic
16 material dominates. These differences in sampling region could explain the lower baseline (dry
17 period) water content observed in Fig. 3.

18 Bowling et al. (2010, 2011) used 30-cm FDR sensors (model CS-615, Campbell Scientific,
19 Inc., Logan, Utah) installed horizontally at 1-cm depth to monitor water content in cyanobacteria
20 found in grasslands close to our site. At this shallow depth and with this longer-length sensor,
21 measured water content and the sensitivity to change in water content could have been negatively
22 affected because of loss of signal above the sensor and sampling of soil without biocrusts below

1 the sensor. Castillo-Monroy et al. (2011) used 5-cm-long TDR sensors and EC-5 sensors
2 (Decagon Devices, Pullman, Wash.) installed vertically into the soil in several plots to measure
3 water content. They found that the sensor provided reasonable estimates of volumetric water
4 content at their field site, but their sensors may have sampled some biocrusts and soils below
5 where biocrust is concentrated. Zhang et al. (2015) used 20-cm-long (Theta®) probes to measure
6 water content of biocrusts and subsoil in the Tengger Desert of China.

7 Although these researchers showed significant relationships between respiration rates and
8 water content, the peak water content values of $< 0.20 \text{ cm}^3 \text{ cm}^{-3}$ (for all sites) was about 50% of
9 the laboratory measurements using the same material. It is reasonable to assume that small
10 precipitation events that wet the near-surface material would be missed using these longer
11 sensors, and that DPHP technology could improve upon the monitoring of smaller precipitation
12 events.

13 In general, researchers relying on horizontally installed TDR and FDR sensors should
14 consider the potential loss of electromagnetic signal for sensors shallower than ~2.2 cm for TDR
15 and ~6 cm for FDR (see Table 2 by Vaz et al., 2013), versus the potential loss of detection of
16 smaller precipitation events that will wet only a portion of the near-surface soil. Even for larger
17 precipitation events, the horizontal installation of TDR and FDR sensors often results in only
18 half of the soil surrounding the sensor being wet (soil below the sensor is often dry), leading to
19 biased low water content values at the surface and an inability to capture rapid drydown of the
20 soil surface in arid environments. Operational limitations for the DPHP sensors include a higher
21 level of post-processing needs and a need for greater care in sensor installation, but in general
22 appear to be fewer when used in near-surface environments.

Estimating carbon fluxes: Understanding soil moisture is essential for estimating C fluxes in biocrusts, whether for upscaling plot-based results, improving model predictions, or allowing extrapolation of laboratory results to field conditions. For example, laboratory measures of respiration and photosynthesis in field-collected *Collema tenax* samples (from close to our study site) showed maximum CO₂ exchange of ~3.5 μmol m⁻² s⁻¹ at a water content of 0.7 g g⁻¹ (equivalent to ~1 mm water addition to biocrusts), with a large decrease at higher (likely due to water saturation) and lower (due to drying) water content (Lange et al., 1998). Brostoff et al. (2005) measured the gas-exchange rates of cyanobacterial (*Microcoleus vaginatus*)-dominated biocrusts from the western Mojave Desert, USA. After controlling for moisture, light, temperature, humidity, and ambient CO₂, they found a peak in photosynthetic activity (~1.5–2.5 μmol CO₂ m⁻² s⁻¹) when gravimetric water content neared 0.20 g g⁻¹, with a relatively narrow reduction on both sides of the peak.

When we combined our soil water content measurements with laboratory biocrust gas-exchange curves from Grote et al. (2010), we estimated a net negative C flux from biocrusts of 69 and 76 g C m⁻² in control and heated plots, respectively, from early April through mid-September 2009. Using automated chambers at this same field site, Darrouzet-Nardi et al. (2015) reported cumulative C losses of 47 and 40 g C m⁻² in spring and summer 2006 and 2007, respectively, for the control plot, and 52 and 44 g C m⁻² during those same times in the heated plots. They monitored water content using the same FDR sensors compared in this study, but reported on C fluxes in conditions of “wet” versus “dry” soil, at a cutoff of 0.05 cm³ cm⁻³ and without directly attributing C fluxes to specific values. The close similarity of these results to the

study reported here indicates that water content measurements from DPHP sensors can be combined with laboratory gas-exchange curves to reflect field conditions.

5. CONCLUDING REMARKS

DPHP sensors show promise as a technology for measuring biocrust water content. We demonstrated that DPHP measurements target the biocrust and avoid either sampling soil deeper than the biocrust material or than the shallower depths, where a portion of the electromagnetic signal extends above the soil–air interface. By using a sensor that interrogates only nearer-surface material, we can detect smaller precipitation events and, thus, the influence of these smaller events on C dynamics. The DPHP method also provides a physical quantity of water content, expressed on a volumetric basis, which could end the need to express biocrust water content in terms of precipitation equivalent and in units of length (see, for example, Lange et al., 1998; Lange, 2002; Weber et al., 2016). With the availability of measurement devices that focus on the biocrust material itself, empirical expressions for water content can be replaced by a physical quantity that is easier to manage and manipulate, especially when considering water dynamics during seasonal drydown and immediately after precipitation events. Physical expressions of volumetric water content would also improve data input to models of soil processes and their influence on biological processes (Vereecken et al., 2016).

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FIGURE CAPTIONS

Fig. 1. Location of FDR (blue numbers) and DPHP sensors (yellow numbers) in (a) control plot 1, and (b) heated plot 2. FDR sensors were installed horizontally at depth of 5 cm.

Fig. 2. Plots of data observed by Grote et al. (2010) (left column) and estimated using equation 2 (right column), showing temperature and relative saturation for gross photosynthesis (top row), dark respiration (middle row), and net photosynthesis (bottom row).

Fig. 3. Average water content measurements for control and heated plots, using DPHP (solid line) and FDR (dashed line) technologies. Black stars = precipitation events corresponding to water content data collection.

Fig. 4. Comparison of maximum water content recorded using DPHP and FDR technologies.

Fig. 5. C dynamics of control versus heated plot for (a) entire 160-d monitoring period, and (b) post-winter drydown during first ~30 d.

Table 1

Precipitation events coinciding with water content data collection and peak mean water content measured using different sensor technologies.

Date	DOY	Precip Depth	Mean Peak Water Content Differences ($\pm$ std deviation)			
			DPHP [†]		FDR	
			Control	Heated	Control	Heated
		-- mm --	----- cm ³ cm ⁻³ -----			
4/11/2009	101	2.7	0.102 $\pm$ 0.061	0.117 $\pm$ 0.081	0.024 $\pm$ 0.001	0.032 $\pm$ 0.001
5/2/2009	122	5.7	0.137 $\pm$ 0.080	0.132 $\pm$ 0.066	0.036 $\pm$ 0.005	0.049 $\pm$ 0.004
5/4/2009	124	2.3	0.092 $\pm$ 0.040	0.114 $\pm$ 0.071	0.025 $\pm$ 0.002	0.027 $\pm$ 0.004
5/23/2009	143	9.3	0.170 $\pm$ 0.040	0.119 $\pm$ 0.039	0.047 $\pm$ 0.003	0.070 $\pm$ 0.011
6/26/2009	177	12.1	0.216 $\pm$ 0.376	0.314 $\pm$ 0.069	0.055 $\pm$ 0.006	0.080 $\pm$ 0.009
7/6/2009	187	1.5	0.035 $\pm$ 0.007	0.033 $\pm$ 0.025	0.007 $\pm$ 0.002	0.006 $\pm$ 0.001
7/26/2009	207	6.0	0.218 $\pm$ 0.104	0.298 $\pm$ 0.055	0.048 $\pm$ 0.006	0.067 $\pm$ 0.009
7/28/2009	209	0.9	0.024 $\pm$ 0.046	0.019 $\pm$ 0.003	0.002 $\pm$ 0.006	-0.006 $\pm$ 0.006
8/14/2009	226	3.7	0.121 $\pm$ 0.017	0.113 $\pm$ 0.728	0.035 $\pm$ 0.013	0.033 $\pm$ 0.004
9/13/2009	256	0.7	0.260 $\pm$ 0.062	0.423 $\pm$ 0.076	0.061 $\pm$ 0.004	0.089 $\pm$ 0.011

[†]Vertical and slanted sensors averaged together (note discussion in text regarding lack of statistical differences).

(a)

(b)

1

2

QAe4787

QAe5349

1

2

QAe5350

1

2