The Potential Use of Soil Moisture Sensors for Observing Hydraulic Redistribution Characteristics

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***Abstract*- A field study along a grass-covered hillside in south-western Pennsylvania revealed diel fluctuations in soil moisture measurements resembling hydraulically redistributed water. Further analysis of the measurements over a summer and winter season supports this finding. The observations are analyzed for possible influences due to soil temperature. Temperature influence on the EC-5 soil moisture sensor readings appears to be present at 5 cm in the form of a correlated pattern with temperature, i.e., an increase in soil moisture with temperature. An inversely correlated pattern, i.e., an increase in soil moisture during the nighttime, shown at 40 and 62 cm is present during the summer dry-down periods and absent during the wet winter season. Given the available data, it is likely that more than temperature is affecting the measurements. Significant amounts of water are found to be redistributed compared to amounts transpired (20–60%). Continued research on this subject is recommended.**

Keywords- Hydraulic Redistribution; Soil Moisture Observations; Soil Moisture Sensor Measurements

I. INTRODUCTION

Hydraulic redistribution (HR), previously referred to as "hydraulic lift" [1], is the passive movement of water throughout the soil layers by plant roots. Studies have shown that this movement of water by the plant roots can occur in any direction, both vertically and laterally [2–4]. HR has been observed in over sixty plant species spanning a variety of plant types (from herb and grasses to shrubs and trees) [5–7] and over a range of environmental conditions (from the Kalahari Desert to the Amazon Rainforest) [3, 6–8].

The movement of water throughout the soil layers by plant roots can be explained by the cohesion theory for water transport [9]. This theory states that water moves through a plant in a continuous column from the roots to the leaves. Water is pulled upward by the difference in water potential between the boundary layers of the roots in the soil (where they are in contact with soil moisture) and the leaves in the atmosphere (where it is dry with relatively low water potential). Soil moisture is absorbed through the root system. Active transpiration (driven by photosynthesis) releases moisture from the leaves into the air. This causes tension in the water column at the surface of the leaf which is transmitted to the water column in the stem and subsequently down to the roots. The cohesive strength of the water molecules maintains the continuous water column within the plant as the potential gradient drives the movement upwards.

This theory can still be applied when the atmospheric boundary layer is closed off to the plant, e.g. when the plant's leaf stomata are closed (e.g., nightly or during heavy cloud cover) [10, 11] or following leaf senescence (e.g., seasonally) [12]. In this circumstance, the potential gradient is no longer between the moist soil and the dry air; rather, it exists between the various soil layers where the plant root system is distributed. Water is distributed by the plant roots, within soil layers containing the plant roots, from relatively wet (e.g., higher water potential) to relatively dry (e.g., lower water potential) regions.

Although HR is a phenomenon that has been studied for decades, little is known regarding the greater impacts this process has on the environment. It is understood that the presence of hydraulically redistributed water (HRW), i.e., water transported during HR, can alter plant-to-plant interactions [5] as well as mitigate the effects of drought [6]. While these studies are focused on the local effects, the large-scale significance is still being investigated. A recommended first step is to increase the number of HR observations with regards to various plant species and environmental conditions [13]. Observations help improve model simulations attempting to capture the HR process. Improved simulations can help answer questions regarding the large-scale influence of hydraulically redistributed water.

Most observations in the past have been done measuring Deuterium isotope traces [3, 4, 6, 14], sap flow [2, 7, 8, 15], and soil moisture and soil water potential [6, 10, 16]. The Deuterium labeling method promotes HR by providing spatial heterogeneity in the local soil water content; however, it does not allow for persistent long-term measurements over natural wetting and drying periods. Sap flow measurements, while providing specifics on a plant's water dynamics, require access to the plant's root system. Reaching the plant's root system may cause disruption in the soil layers around the plant or destruction of fine roots in the shallow soil layers. The complexity of plant root systems also makes it difficult to know which roots to actively monitor. Soil moisture sensors, albeit inexpensive and generally non-disruptive to the soil column during installation, only provide point measurements in the soil. Due to the dynamic nature of HR, it is difficult to predict at what location and at what depth HR will occur.

While each observation method has its own benefits and drawbacks, soil moisture may be considered the easiest and most convenient approach for making HR observations. Multiple measurement locations and depths can be monitored to overcome the observational limitation that soil sensors have. Careful analysis of soil moisture measurements must be made to discern signal anomalies, temperature artifacts and sensor failures from actual soil moisture patterns.

Results from a soil moisture field study located on a hillside at an experimental environmental remediation location (i.e., a unique soil environment) revealed diel patterns at two locations during periods of dry-down. It is hypothesized that the soil moisture patterns at 40 and 62 cm are the direct measurement of the HR processes. The purpose of this study is to: 1) exhibit the characteristics of hydraulic redistribution when measured with soil moisture sensors; 2) quantify HRW based on soil moisture measurements; and 3) expand the number of observations (both in terms of plant species and soil types) of HR. In addition, to compliment the first goal of this study, an analysis of temperature as a potential artifact on the sensor measurements was conducted. Temperature influence on soil moisture sensors is the primary topic of opposition to these measurements. The results of the temperature analysis for this field study do not discredit the soil moisture fluctuations as being the result of HRW.

II. METHODS AND MATERIALS

A. *Field Description*

The field study is located along a 0.81 ha hillside in the city of Mather, Pennsylvania, U.S.A. The hillside is a part of the remaining spoil heap from the Mather Collieries Plant which began its forty-six year coal mining operation in 1918. In 2006, the Department of Environmental Protection (DEP) and Alcoa (an aluminum manufacturing company) suggested a soil reclamation process using a new manufactured soils concept.

The northern-facing hillside was graded to approximately 33% (18.4° slope) and divided into four 0.20 ha experimental plots. Each plot received a different remediation layer. This study focuses on two plots (i.e., Plots 2 and 3) amended with Alcoa's alkaline bauxite residue (a waste product of the aluminum manufacturing process). The remediation layer on Plot 2 (62 cm deep) consists of a mixture of 10% bauxite residue and 90% coal refuse (by weight). The remediation layer on Plot 3 (90 cm deep) consists of a mixture of 10% bauxite residue, 5% compost, and 85% coal refuse.

In the spring of 2009, the hillside was hydro-seeded with a vegetation mix which included (but is not limited to) tall fescue (*Festuca arundinacea*), redtop grass (*Agrostis gigantea*), and birdsfoot trefoil (*Lotus corniculatus*). During the end of the first growing season, a 90 cm excavation was made in both of the plots to determine the rooting depths of the vegetation. For both Plots 2 and 3, roots were found growing throughout the excavated depth (i.e., ≥90 cm rooting depth).

B. *Measurements*

Soil moisture sensors were used to measure localized volumetric changes in the water content of the soil. These measurements were made using EC-5 soil moisture sensors (Decagon Devices, Inc.). The EC-5 is a capacitance-style soil moisture sensor. It is rapidly charged and discharged using a 70 MHz frequency to create an electromagnetic field. This magnetic field uses the surrounding soil as a capacitor. The charge time of the capacitor (i.e., the soil surrounding the sensor) is related to the dielectric permittivity of the soil. The dielectric permittivity of the soil is based on the soil's composition (e.g., air, water, and solids); however, it is most sensitive to the soil's water content. This allows the dielectric permittivity to be related to the soil's volumetric water content (VWC). A linear relationship between the measured dielectric permittivity and the VWC of the soil has been developed by Decagon Devices for mineral-based soils. It was used in this study and is available in Section 4 of the EC-5 User's Manual (http://www.decagon.com/assets/Uploads/EC-5-Manual.pdf).

To provide side-by-side temperature and soil moisture measurements, the 5TM (Decagon Devices, Inc.) water content and temperature sensor was used. The 5TM sensor uses the same theory of operation as the EC-5; however, this sensor includes a thermistor for measuring the soil's temperature, has a built-in microprocessor (i.e., digitized measurements), and an improved calibration method for measuring dielectric permittivity. The dielectric permittivity, for the 5TM sensor, is related to VWC using the Topp equation [17].

In the spring of 2010, EC-5 soil moisture sensors were installed at three depths (5, 40, and 62 cm) on both Plots 2 and 3. One sensor was installed at each of the three depths (i.e., three sensors per plot, six sensors in total for both plots). The EC-5 sensors were connected to EM50 data loggers (also by Decagon Devices, Inc.) which sampled the sensors every 30 minutes.

In the spring of 2012, two additional 5TM sensors were installed on Plot 2 at two depths (40 and 62 cm). These two sensors were attached to their own EM50 data logger and located within three meters of the pre-existing EC-5 soil moisture sensors. The purpose of this installation was to provide insight on the thermal gradients existing within the remediated coal refuse layer for comparisons to the soil moisture fluctuations.

Meteorological data were provided by a personal weather station (KPACLARK3) located approximately three kilometres away from the study area. This weather station (Davis Vantage Pro2) is a part of Weather Underground's world-wide weather station network. The weather station's measurements are recorded and uploaded to an online database where they can be downloaded free of charge (http://www.wunderground.com/weatherstation/WXDailyHistory.asp?ID=KPACLARK3).

III. RESULTS

Measurements are presented for a 30-day period during the summer of 2010 (Fig. 1). The atmospheric temperature during this time ranged from 4–35 ℃. The precipitation time series (Fig. 1a) shows little rainfall during this period until 16 September when almost 5 cm of rain fell with intensities as high as 0.6 cm·hr^{-1}. Earlier rainfalls on 21–23 August produced spikes in the soil moisture curves especially at 5 and 40 cm (Fig. 1b and 1c). During the following weeks, the soil moisture curves gradually dry down. In Plot 2 (Fig. 1b) the surface soil moisture (5 cm) dries down considerably more (i.e., less than 0.1 VWC) when compared to the surface of Plot 3 (Fig. 1c). At 40 cm, both plots begin around the same water content level (approximately 0.15 VWC). However, Plot 2, which has a 62 cm remediated layer, retains more moisture at the 40 cm depth than Plot 3, which has a 90 cm remediated layer. The higher soil moisture content in Plot 3 is shown at the deeper 62 cm depth, whereas in Plot 2 the 62 cm depth, near the lower boundary of the remediation zone, remains generally constant. The soil moisture measurements at both 40 and 62 cm in Plots 2 and 3 are between 0.08 and 0.18 VWC before the September rainfall.

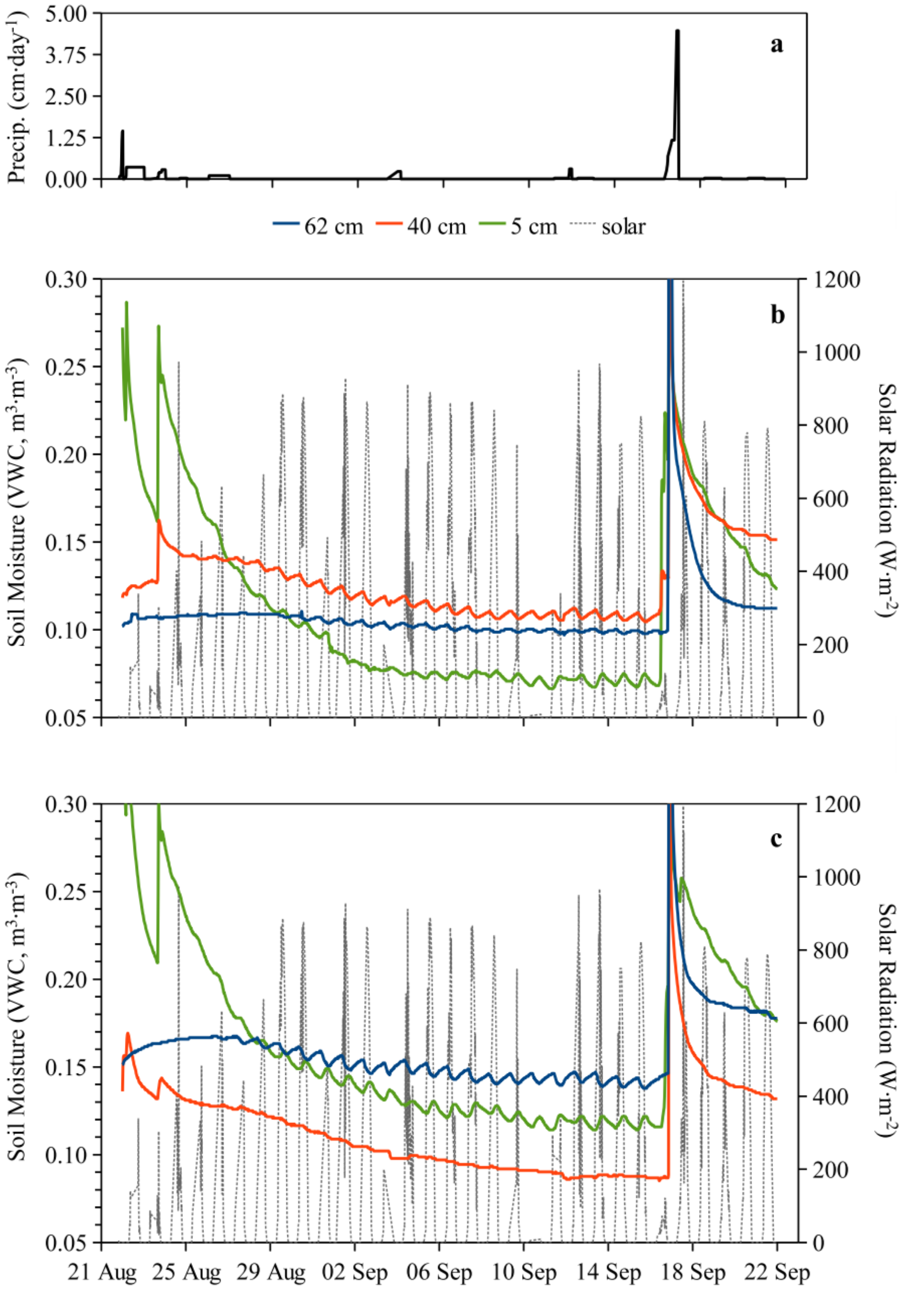

Fig. 1 Summer 2010 measurements of (a) daily precipitation amounts (cm·day-1); (b) soil moisture (VWC, m^3·m^{-3}) measured at three depths (5, 40 and 62 cm) for Plot 2 and solar radiation (W·m^{-2}) measured at the personal weather station; (c) soil moisture (VWC, m^3·m^{-3}) measured at three depths (5, 40 and 62 cm) for Plot 3 and solar radiation (W·m^{-2}) measured at the personal weather station

During the dry-down period in both Plots 2 and 3, diel fluctuations are seen in the soil moisture curves. At 5 cm, daytime soil moisture (indicated by positive solar radiation) increases while nighttime soil moisture decreases. At 40 and 62 cm, during the same dry-down period, there is a negative correlation between the daylight hours and soil moisture. The 40 cm fluctuations are more prevalent than at the deeper 62 cm in Plot 2, while in Plot 3 there is little or no indication of diel fluctuations at 40 cm.

Additional measurements are presented for a 30-day period during the winter of 2010–2011. The atmospheric temperature over this time ranged from -22–16 ℃. A significant precipitation event occurred on 1 January (Fig. 2a) which produced over 1 cm of rainfall with rates as high as 0.66 $cm \cdot hr^{-1}$. Another precipitation event occurred over 18–19 January with long periods of light rain. The sudden jump in soil moisture at 40 and 62 cm in Plot 2 (Fig. 2b) occurs just after nightfall on 18 January when there is no significant recorded rainfall. There is no such jump indicated in Plot 3 (Fig. 2c) at this time.

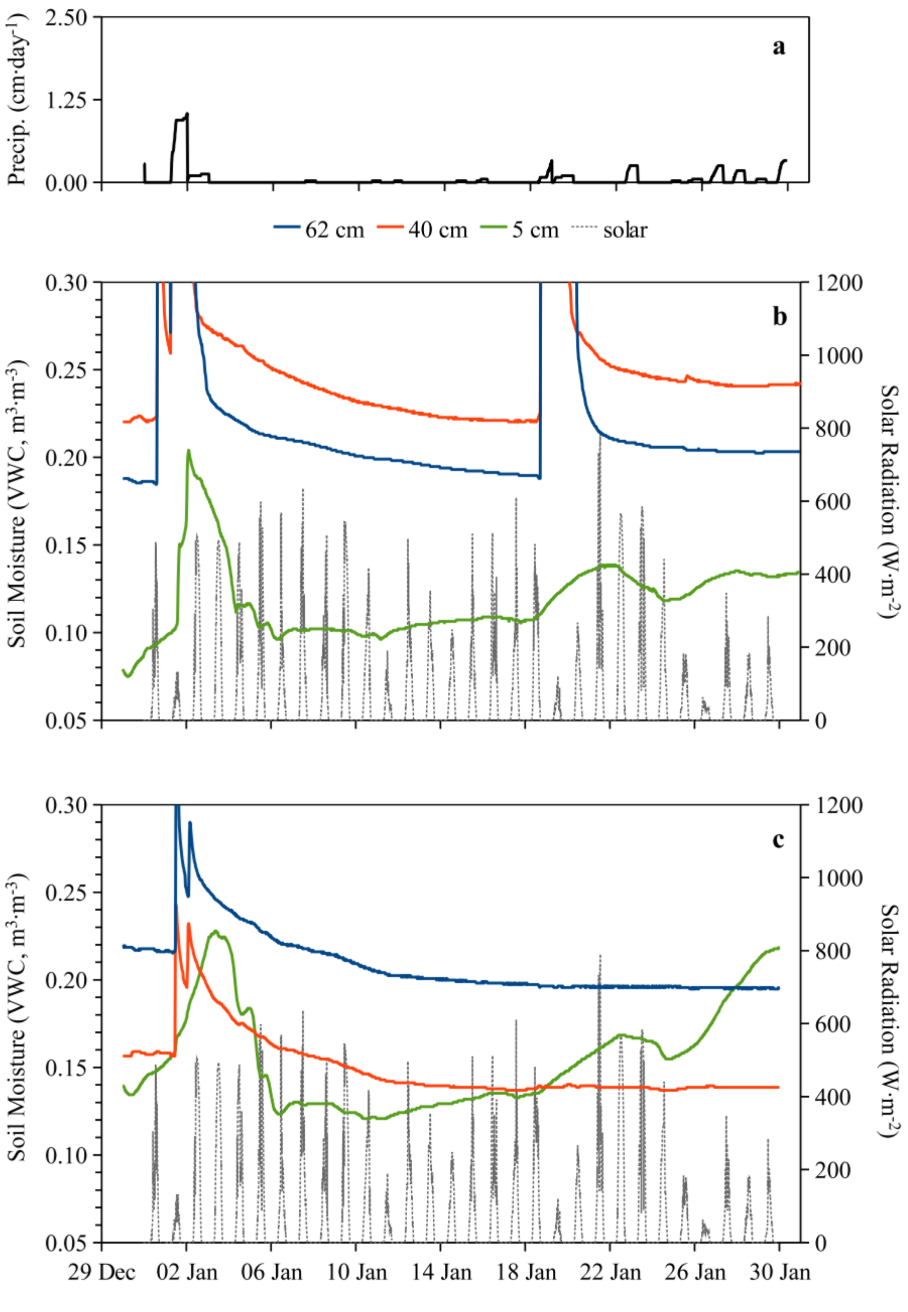

Fig. 2 Same measurements as Fig. 1 but during the winter of 2010–2011

During the two week dry-down period between these precipitation events, the soil moisture at 40 and 62 cm gradually decreases. The soil moisture measurements at 62 cm in both Plots 2 and 3 are approximately the same (between 0.18–0.28 VWC). The soil moisture at 40 cm is once again higher than at 62 cm in Plot 2 and lower than at 62 cm in Plot 3. The surface soil moisture (5 cm) gradually increases over the same period in both Plots 2 and 3.

IV. DISCUSSION

A Evidence Supporting HR Measurements

The summertime diel fluctuations show, at 40 and 62 cm in both Plots 2 and 3, an expected daytime decrease in soil moisture, which can be attributed to transpiration by the vegetation (Fig. 1). The counter-intuitive nighttime increases in soil moisture may be attributed to redistributed water by the vegetation's root system. Similar diel fluctuations have been attributed to redistributed water by [16] at the end of the dry season in a tropical forest in Eastern Amazonia up to a depth of 200 cm and by [18] during dry-down periods at the Cook Experimental Farm at Washington State University at depths up to 150 cm.

The diel fluctuations are stronger at 40 cm in Plot 2 (Fig. 1b) and at 62 cm in Plot 3 (Fig. 1c). Due to depth differences in the remediated layers, it can be assumed that little root growth penetrated past 62 cm in Plot 2. However, due to the deeper 90 cm remediation layer in Plot 3, plant roots may be readily growing at 62 cm and as a result a stronger soil moisture pattern is shown deeper in the soil column.

The absence of diel fluctuations during the winter (Fig. 2) may be due to the higher soil moisture levels at 40 and 62 cm compared to the levels of soil moisture in the summertime (Fig. 1). The lack of fluctuations may also be due to the inactivity of the vegetation as the grass goes into winter dormancy. The absence of fluctuations at the surface (5 cm) may be caused by the smaller differences between the maximum daytime and minimum nighttime atmospheric temperatures.

In terms of temperature, much debate exists over the influence of ground temperature on soil moisture sensor measurements. Thorough studies have been conducted concerning the effects of temperature on soil moisture sensor measurements [19, 20]. As mentioned previously, the EC-5 soil moisture sensor operates at a high frequency (70 MHz) which provides a generally lower thermal sensitivity than its predecessors (e.g., EC-10 and EC-20 sensors). Controlled laboratory experiments showed thermal responses for this type of sensor in air and water to range from 0.000116 $m^3 \cdot m^{-3} \cdot ℃^{-1}$ to 0.000369 $m^3 \cdot m^{-3} \cdot ℃^{-1}$, respectively [19].

In Fig. 1 there is a positive correlation between day and nighttime hours and soil moisture increases and decreases near the surface (5 cm) while there is a negative correlation at the deeper layers (40 and 62 cm). A positive correlation between temperature and soil moisture (measured from soil dielectric permittivity) is possible [21] but has not been shown for this type of soil media. Within the same soil media, it is possible to have either a positive or negative correlation between soil moisture sensor measurements and temperature [20]; however, it is unlikely that temperature and soil moisture will simultaneously exhibit both a positive and negative correlation between one another. It is possible that the gradient of soil temperature with respect to depth can explain the opposing fluctuations. This was analyzed using the Kusuda model [22]. However, due to the unique soil conditions in this study, thermal diffusivity (α) values based on literature and soil composition were found in the range of 4–48 $cm^2 \cdot hr^{-1}$. Correlation coefficients between de-trended and normalized thermal sinusoidal curves (i.e., Kusuda) and soil moisture measurements at the three depths produced varied results, ranging from strongly positive to strongly negative and no correlation at 40 and 62 cm (the correlation at the 5 cm depth does not change significantly with α), and were therefore inconclusive (see Table 1 for examples).

TABLE 1 SELECTED CORRELATION COEFFICIENTS BETWEEN MODELED SOIL TEMPERATURE BASED ON DIFFERENT THERMAL DIFFUSIVITY VALUES (Α) AND SOIL MOISTURE MEASUREMENTS AT TWO DEPTHS OVER A FIVE-DAY DRY-DOWN PERIOD (29 AUG – 02 SEP) FOR TWO PLOTS IN 2010

Plot 2			**Plot 3**		
α ($cm^2 \cdot hr^{-1}$)	**5 cm**	**40 cm**	**α ($cm^2 \cdot hr^{-1}$)**	**5 cm**	**62 cm**
4.07	+0.26	-0.87	8.89	+0.90	-0.00
6.66	+0.34	-0.00	10.3	+0.91	-0.95
13.0	+0.41	+0.87	17.2	+0.91	-0.00
34.5	+0.47	-0.00	34.0	+0.90	+0.95

To investigate this further, soil temperature measurements were added to Plot 2 at 40 and 62 cm during the spring of 2012 (Fig. 3). The soil temperature measurements show a distinct temperature gradient between the two measured depths (Fig. 3b). At 40 and 62 cm, soil moisture diel fluctuations are present, which are similar to the summer of 2010 findings (Fig. 1b). In the soil temperature measurements, prominent diel fluctuations are seen at 40 cm while little or no diel fluctuations are present at 62 cm. This suggests that something other than temperature is influencing the soil moisture pattern at 62 cm.

At 40 cm, the amplitude of the temperature fluctuations is approximately 0.17 ℃, while the amplitude of the soil moisture fluctuations during the same time is approximately 0.002 $m^3 \cdot m^{-3}$ (Fig. 3b and 3c). Therefore, the implied influence of temperature on the soil moisture measurements is 0.0118 $m^3 \cdot m^{-3} \cdot ℃^{-1}$ which is a factor of 100 greater than the published values for this type of sensor [19]. This suggests that there is something more than just temperature influencing the soil moisture measurements at 40 cm.

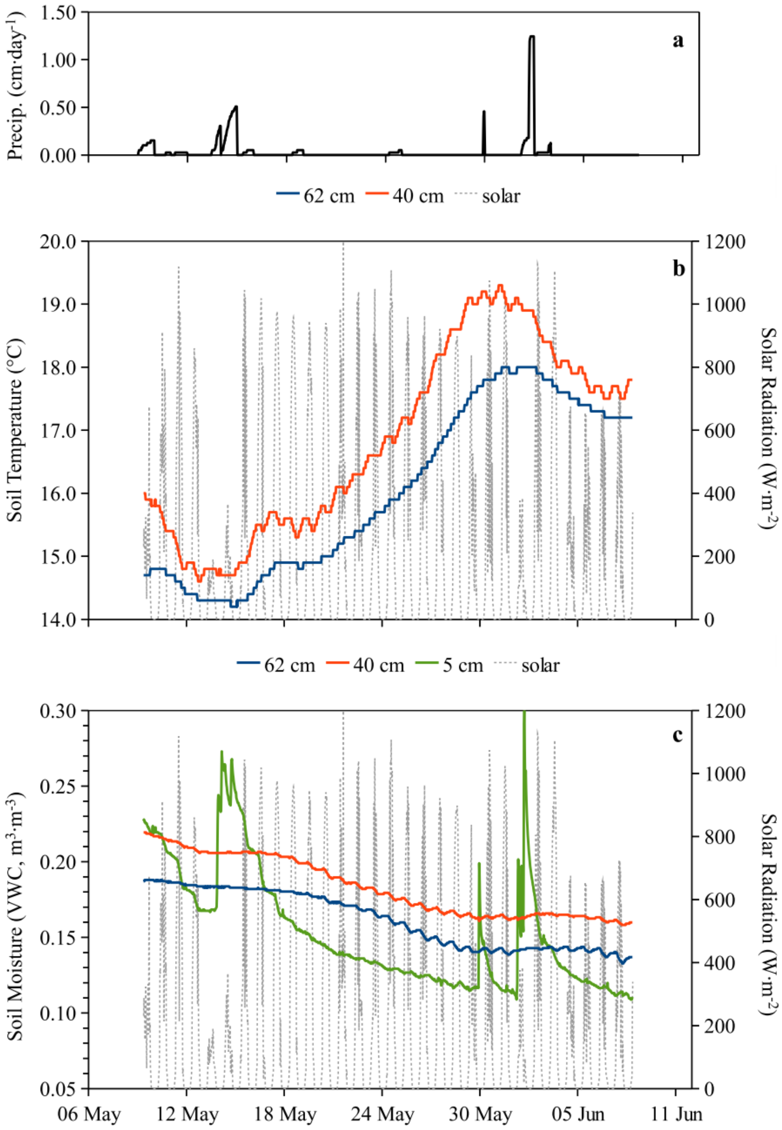

Fig. 3 Spring 2012 measurements of (a) daily precipitation amounts (cm·day^{-1}); (b) soil temperature (℃) measured at two depths (40 and 62 cm) for Plot 2 and solar radiation (W·m^{-2}) measured at the personal weather station; (c) soil moisture (VWC, m3·m^{-3}) measured at three depths (5, 40 and 62 cm) for Plot 2 and solar radiation (W·m^{-2}) measured at the personal weather station

B Evidence Opposing HR Measurements

Despite the evidence of HR (Figs. 1 and 3), there are also some factors which oppose the idea that this is indeed the HR phenomenon. The first example is the correlation between the temperature measurements and soil moisture at 40 cm. The soil moisture and temperature measurements (Fig. 3b and 3c) were de-trended and normalized in the same fashion as presented in Table 1. A positive correlation was calculated between these two series (Pearson correlation coefficient, $\rho = 0.742$) indicating the possibility that temperature is the main influence on the diel fluctuations at 40 cm.

The 5TM sensor responsible for the temperature measurements (Fig. 3b) also measures the VWC of the soil. The soil moisture measurements made at 40 and 62 cm by the 5TM sensors (not shown) did not exhibit the same diel fluctuations as the EC-5 sensors (Fig. 3c). The difference between the soil moisture measurements made by the 5TM sensors compared to the EC-5 sensors may be due to either the different calibration methods between the 5TM sensor and the EC-5 sensor or the microprocessor onboard the 5TM sensor (i.e., possible signal smoothing). While the two sensor types may have differing sensitivities to temperature, it cannot be said for certain that the EC-5 sensors are monitoring HR while the 5TM sensors are not. On the other hand, this result does not suggest that the HR process did not exist during either of the monitoring periods (Figs. 1 and 3). The soil moisture is wetter and the fluctuations are smaller during the spring of 2012 (Fig. 3) than during the drier summer of 2010 (Fig. 1).

There exist a number of variables that cannot be accounted for due to the heterogeneous nature of the soil type in which this study is set. Despite these shortcomings, the diel soil moisture fluctuations, with temperature measurements, present a unique study of the HR process.

C Hydraulically Redistributed Water

One of the unique opportunities soil moisture measurements of the HR phenomenon presents is the ability to quantify hydraulically redistributed water (HRW) over time. During spring and summer dry-down periods (i.e., periods without precipitation) daytime decreases in soil moisture are assumed to be attributed to plant water use or seepage, while the nighttime increases in soil moisture are assumed to be caused by HRW. For the purposes of this study, quantification of HRW is presented as the ratio of the nighttime increments to the daytime decrements in soil moisture. This is exemplified by the subsequent rises and falls in the soil moisture curve.

The maximum and minimum daily soil moisture values were identified for the soil moisture curves during the summer of 2010 (Figs. 1b and 1c) and spring of 2012 (Fig. 3c). The HRW was calculated as the rise in soil moisture content from the previous night's minimum to the current day's maximum (i.e., the total nighttime increase). The transpired water was calculated as the decline in soil moisture content from the current day's maximum to the current night's minimum (i.e., total daytime decrease). This ratio tends to increase as the soil moisture content decreases. A multiple regression strategy for correcting temperature influences on soil moisture measurements [20] was performed on the 2012 measurements. The ratios of daily HRW from the corrected and uncorrected soil moisture curves are given in Table 2, which shows that a significant amount of water has been redistributed even with the correction during the dry period (i.e., summer 2010). Similar results were shown in [16] where a figure of diel soil moisture measurements at 62 cm depicts the estimated ratio of HRW to transpired water ranging from 20–29%.

TABLE 2 AVERAGE RATIO OF DAILY HRW TO DAILY TRANSPIRED WATER USING SOIL MOISTURE MEASUREMENTS (ORIGINAL AND CORRECTED FOR TEMPERATURE INFLUENCES) FROM MONITORING PERIODS DURING THE SUMMER OF 2010 AND SPRING OF 2012

		Summer 2010 (29 Aug–2 Sep)	Spring 2012 (19–30 May)	
		Uncorrected	**Uncorrected**	**Corrected**
Plot 2	40 cm	37%	30%	19%
	62 cm	50%	28%	24%
Plot 3	40 cm	0%		
	62 cm	61%		

V. CONCLUSIONS

This study presents measurements of soil moisture in a unique soil environment. The diel fluctuations in the measurements were analyzed in terms of both vegetative cover and thermal gradient influence. The observations, which are perceived to be HR by grass roots, are scrutinized under the possibilities of being both HR and sensor anomaly. While there are important factors supporting both sides of the argument, given the available data, it is likely that more than just temperature is producing the diel fluctuations. Because temperature poses the main influence on the findings, both soil moisture and soil temperature measurements (taken at the same time and depth) are needed to study HR.

There are several benefits for using soil moisture measurements for capturing data on the HR phenomenon: it is a low cost method, it provides long-term sampling, and it allows for the opportunity to quantify HRW. For the time periods analyzed in 2010 and 2012, the average ratio of HRW to transpired water was found to be significant (20–60%). Based on the results of this study, it is recommended that more research be conducted to definitively confirm that HR is observable in soil moisture measurements since it does account for a significant amount of water compared to that transpired.

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