NAMIBIA UNIVERSITY OF SCIENCE AND TECHNOLOGY

Successful rehabilitation of dryland mined areas requires knowledge of soil moisture patterns over long periods and large areas: Comparing relatively cheap iButtons with established methods for measuring soil moisture

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Successful rehabilitation of dryland mined areas requires soil moisture monitoring to optimize the use of water

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Introduction

Mining is an important cause of disturbance to ecosystems. Ecological disturbances in drylands (defined as an area with an aridity index < 0.65) cause a number of challenges for the restoration of ecological structure and function (Aronson et al., 1993), most of which are related to the high variability of water availability and accessibility to organisms. Disturbance caused by mining exacerbates this effect because it tends to result in a loss of all topsoil and with that also the valuable biological factors that support the establishment of organisms and the development of structure and function. To colonizing organisms it thus presents a novel, biologically impoverished substrate with physical properties that makes it largely unsuitable for plant and other organisms' survival and establishment Cooke & Johnson, 2002).

In drylands, a key requirement to understand the likelihood of survival of plants used in rehabilitation is data on soil moisture dynamics which can vary considerably across space and time (Rosenbaum et al., 2012). The amount of moisture in the soil, integrated over time, synthesizes the combined effect of climate, substrate and vegetation on the dynamics of dryland ecosystems (D'Odorico et al., 2007). Data on soil moisture dynamics, at scales from local to small catchment, therefore allows a clearer understanding of how to recover ecological properties that were lost due to mining. These properties are key to being able to manipulate ecosystem changes after disturbance and include factors such as *inter alia* pulsed increases in microbial activity (Frossard et al., 2015), the fine-scale positive feedback effects of vegetation on soil moisture (D'Odorico et al., 2007), and the relationship of plant survival rates to soil moisture variability (Reynolds et al., 2004).

The dynamics of soil moisture that are relevant for restoration – and thus the kind of data that are required – ranges across several spatial scales, from the local, landscape level, which is often inside a mine's immediate sphere of influence, to the small catchment scale, which may extend well beyond the mine's immediate footprint. The same is true for variation across time – an understanding of ecosystem recovery requires knowledge of variation in soil moisture across weeks, seasons and years (Rosenbaum et al., 2012).

Numerous soil-moisture sensor designs exist (Zazueta & Xin, 1994; Mittelbach et al., 2012), most of which use some form of electromagnetic differential as indicator of moisture content, calibrated for specific soil types. All are sensitive (to varying degrees) to soil texture, bulk density and sometimes soil temperature, curtailing their widescale use across many soil types (Leib et al., 2003). Their relatively

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high cost and the fact that most require to be tethered to a logging station of some kind decreases the number of sensors that can be deployed at one time (and thus the spatial granularity of measurement), and the distance that a sensor can be from a data logger (and thus the spatial extent over which they can be used simultaneously).

Box 1: Abbreviations

GWC:	Gravimetric Water Content
RH:	Relative Humidity
TDR:	Time Domain Reflectometry
VWC:	Volumetric Water Content

Commonly available instruments use the capacitance technique or the time domain reflectometry (TDR – Box 1) (Ventura et al., 2010). Both methods use the relatively higher dielectric constant of water when compared to that of soil, to establish a calibrated relationship between changes in voltage and the soil's volumetric water content (VWC). Capacitive sensors measure the apparent moist soil dielectric constant as a function of the charge time of a capacitor buried in soil and requires an empirical calibration equation (Cobos 2006) to describe the relationship between the output voltage and the VWC for each soil. The TDR device propagates a high frequency electromagnetic wave along a cable connected to a parallel conducting probe inserted into the soil. The signal is reflected back to the meter from the end of the probe, and the instrument measures the time between sending and receiving the pulse (Ventura et al., 2010). The accuracy and precision of both types of techniques are affected by salinity, soil type and temperature. Driven largely by their most common use, which is to determine soil moisture for irrigation decisions, a lot of emphasis is placed on absolute accuracy of measurement (Leib et al., 2003) and less on only precision. Remote sensing approaches tend to work better when the spatial scale increases (Bogena et al., 2015), but these also require ground-truthing at scale.

An alternative approach that has been attempted a few times is to measure the relative humidity of soil pore spaces using a low-cost, easily deployable hygrochron. These small devices, known commercially as iButtons (Figure 1), were designed for the measurement of temperature and relative humidity in food transport. The ~17mm diameter iButton can be attached to many surfaces and can log data for various lengths of time depending on the frequency setting. These devices are relatively accurate and provide valuable medium- to long-term data on changes in both temperature and humidity, at least when deployed as designed. Despite some negative reports about using them in soil (Fawcett et al., 2019), they have been used for measuring changes in moisture and humidity in litter (Wang et al., 2015) and soil (Schagen et al., 2021). When measuring in litter, the iButtons would still be fully in contact with the atmosphere (Wang et al., 2015) but when used in soil they measure the relative humidity of pore spaces. The latter presents several difficulties for interpretation of results, as pore spaces can be continuously saturated with moisture even when the soil is relatively dry – the atmosphere within air-dry soil (a gravimetric water content of 2%) has a relative humidity of 98% (Coleman et al., 2004). This, as well as problems with free-water saturation has led to some resistance against its wider use for measuring soil moisture.

Figure 1. An iButton.

However, the iButtons have several potential advantages that make them – at least theoretically – viable contenders worthy of more intensive investigation. These include small size, ability to log data untethered to an external logger and relative low cost. Additionally, soil water potential in drylands is often below the –1.5 MPa that is generally considered to be wilting point for many crop species. All the common methods of measurement of VWC based on the dielectric constant of water struggle to perform at the low water potentials characteristic of drylands, severely restricting our understanding of critical thresholds for plant survival on e.g. mine wastes in the arid zone. It is therefore especially important that we find a solution for in situ measurement of soil moisture in drylands. The measurement of RH, which does not rely on electric potential differences as determined by water behaviour in microscopic pore spaces, could be such a way providing that the limitations can be overcome. It is also theoretically possible that RH will be a more direct indicator of plant-available moisture as it reflects water that is free enough to change into a gaseous phase.

In the current report I compare the values of soil moisture content (in a standardized substrate mixture) measured as VWC, soil RH and gravimetric water content (GWC) over a period of 72 hours in a controlled environment. I additionally compare in-situ estimates of soil moisture, measured as RH and VWC, in a typical garden soil. My overall aim is to use these contrasts to demonstrate the potential for using iButtons for distributed soil moisture monitoring, and to define those aspects of the measurement process that would be amenable to refinement and improvement in an expanded and more controlled experiment. In comparing these three measurement devices, I used GWC as a control trend, reasoning that it is the most accurate indication of the trend in the amount of water molecules by weight in the soil material, notwithstanding the modifying effects of texture and temperature (I did not have access to facilities where soil temperature could be held constant). I thus wanted to determine whether 1) either the soil RH or VWC showed any obvious deviations from the GWC trend, and 2) expecting some issues with the RH measurement, whether these problems were fatal flaws or whether there were some potential solutions given a more comprehensive setup and better facilities.

Methods

I conducted two experiments. In the first, conducted in a controlled environment, I filled four 500 ml clear plastic containers with a 2:1 mixture of ~970 g of washed sand (commercially produced filter sand) and a sandy loam soil obtained from my garden. The garden soil was sieved with a ~3 mm sieve to produce a more homogenous mixture. Two of the containers were saturated with water, receiving ~204 g of water each, while ~150 g of water was added to the other two to create a non-saturated treatment.

Soil water content was measured using:

1) iButton temperature and RH loggers (Figure 1; Analog Devices, Inc[2], USA; model DS1923-F5#, temperature range = –20 °C - +85 °C, relative humidity range = 0 – 100% RH),

[2] https://www.analog.com/en/products/ds1923.html#product-overview

2) Decagon ECH2O EC5 soil moisture meter (Figure 2; METER Group, USA; measuring range of 0 to 100%, at a resolution of 0.001 m^3/m^3 in mineral soils and a generic accuracy of 0.03 m^3/m^3). The EC5, as well as a soil temperature sensor and air temperature and RH sensors (Figure 4d) were connected to a HOBO Mirostation data logger.
3) An A&D FX 1200i electronic balance (A&D Company, LtD, Tokyo, JAPAN; with an accuracy of 0.01 g and maximum capacity of 1,220 g). This balance is frequently calibrated by the technicians at the Engineering laboratory at NUST.

Figure 2. The probe of the Decagon ECH2O EC5.

All four of the substrate containers received an iButton, which was installed in a custom-made plastic holder constructed from electrical conduit connector and pipe such that the iButton's measuring hole was held facing a cylindrical volume of ~11 mm deep and 20 mm diameter (Figure 3). The open, cylindrical volume was covered with two layers of a fine nylon mesh to prevent ingress of soil and to provide a space much larger than the soil's pore spaces into which soil water vapour could diffuse (Figure 4). Two of the containers each also received an EC5 soil moisture probe (Figure 2, Figure 4d, set to measure every two minutes) and a soil temperature probe.

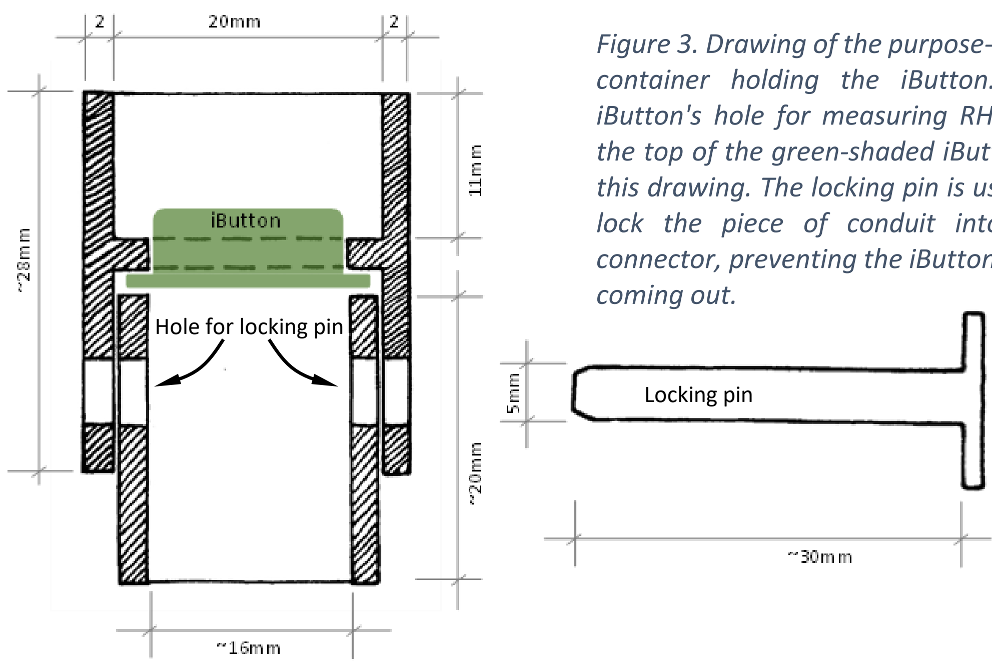

Figure 3. Drawing of the purpose-made container holding the iButton. The iButton's hole for measuring RH is at the top of the green-shaded iButton in this drawing. The locking pin is used to lock the piece of conduit into the connector, preventing the iButton from coming out.

The two soil containers without the EC5 sensors were weighed on the FX1200i electronic balance at approximately half-hourly intervals for the first ~24 hours, and at hourly intervals thereafter for a total of 88 hours. For the last few hours, the successive decrease in weight between measurements was less than 0.004 to 0.006 $g.minute^{-1}$. One large standing fan and one small desktop fan were trained on the workbench with the soil containers and were in continuous operation for the full duration of the experiment, being switched off only for weighing.

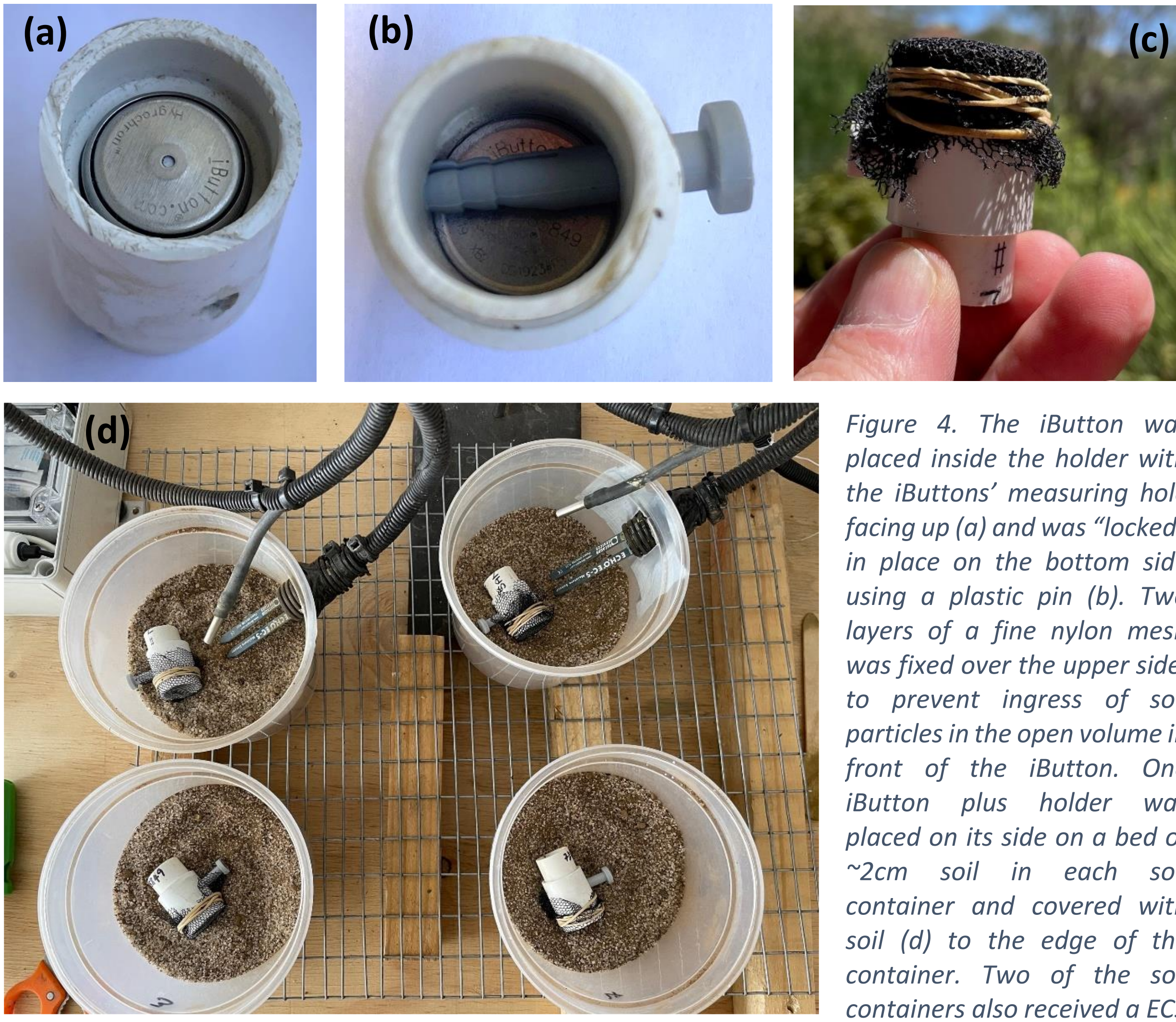

Figure 4. The iButton was placed inside the holder with the iButtons' measuring hole facing up (a) and was "locked" in place on the bottom side using a plastic pin (b). Two layers of a fine nylon mesh was fixed over the upper side, to prevent ingress of soil particles in the open volume in front of the iButton. One iButton plus holder was placed on its side on a bed of ~2cm soil in each soil container and covered with soil (d) to the edge of the container. Two of the soil containers also received a EC5

In the second experiment, I installed, in two locations in my garden, two iButtons and one EC5 into a soil profile (both the temperature and soil moisture probes). The garden soil was thoroughly dry, having not received any rain in the preceding month. At location 1 I wetted the soil to saturation and allowed the moisture to drain through the profile and to dry out to less than field capacity before installing the sensors. At location 2 the extremely dry soil forced me to wet three small patches using a spray bottle, one for each of the sensors, to allow installation. These wet patches influenced the start of the measurements but were relatively small and shallow and thus dried out quickly.

Figure 5. Experiment 2. Installation of the Ec5 with its associated sensors and the two iButtons on a dry soil profile in my garden. The two solid white arrows are pointing t the location of two iButtons which were inserted with the open end of the holder pushed snugly against the soil. The dashed white arrow points to the location of the ECH2O EC5 soil moisture sensor and soil temperature probe. The black arrow points to the solar shade for an air temperature and RH sensor. The latter are fixed above the HOBO Microstation data logger. The dark patches are wet soil, necessitated to allow the placement of the sensors in the hard dry soil. These wet patches dried out within 12 hours. The whole setup was shaded using a small brown polypropylene canvas. This set of measurements were contrasted with a similar setup in soil that was just below field capacity.

Data were downloaded using the proprietary software for the EC5 and iButtons, and manually entered in a spreadsheet in the case of the weight data. None of the measurements could be started at precisely the same time. All time series were thus standardized to an idealized measuring period to allow direct comparisons of measurement profiles over the same time period. Because of the low levels of replication that was possible in this experiment, no statistical methods were used to compare any of the trends.

Results

In Experiment 1, the EC5 delivered astounding results. Although the experiment was not set up to test linearity, the clear congruence between the GWC and VWC (Figure 6) suggests that the method is reliable, at least in the soil moisture range that I tested. For unknown reasons the EC5 tracked the rate of loss of water better when the soil was properly saturated at the start of the experiment than in the relatively dry soil, where the rate of change in weight was marginally slower than the rate of change in VWC towards the end of the experiment (Figure 6). This might have been caused by the lack of calibration of the EC5 sensor to the specific substrate I used, but the low level of replication (n = 2) prevents any further speculation as to the cause of this.

The two iButtons in both treatments showed large differences in their absolute values of RH, although their trends appear to be similar (Figure 6). This is more so in the non-saturated treatment than in the saturated one, where the one iButton showed an exaggerated version of the trend in the other one (Figure 6).

The % RH stayed at 100% for half the time even though both GWC and VWC had already started dropping (Figure 6). Despite this, % RH started declining sometimes quite rapidly after that (Figure 6). The RH values dropped as low as 45% in the saturated treatment.

Soil temperature as measured by the temperature sensor attached to the EC5 setup and the sensor on the iButton tracked each other perfectly, but appeared to have only a weak relationship with levels of % RH and none with VWC in either treatment (Figure 6).

Results in Experiment 2 partly confirmed the results from experiment 1, and showed added environmentally-induced variation. The iButtons again struggled to get below 100% RH, especially in the wet soil treatment (Figure 7). In the wet soil the iButtons took more than 50% of the full time period to detect the beginning of the decline in % RH, while VWC started dropping almost immediately (Figure 7b). In the dry soil, both the EC5 and the iButtons accurately reflected the starting condition where the soil had to be wetted to install the sensors, but soon generally dry soil condition (Figure 7a).

The daily pattern in both VWC and %RH reflected the diurnal cycle of a drop and then rise in ambient temperature (Figure 7). This caused a similar but opposing daily cyclical pattern in RH and VWC, with %RH decreasing and VWC increasing with increasing ambient temperature (Figure 7). This correlation with temperature was clearly evident in the dry soil treatment, but less so in the wet soil treatment, except for VWC (Figure 7).

In both experiments, VWC dropped to below zero, except in the wet soil treatment in experiment 2. This reflects the lack of proper calibration of the sensor in the soil material we used.

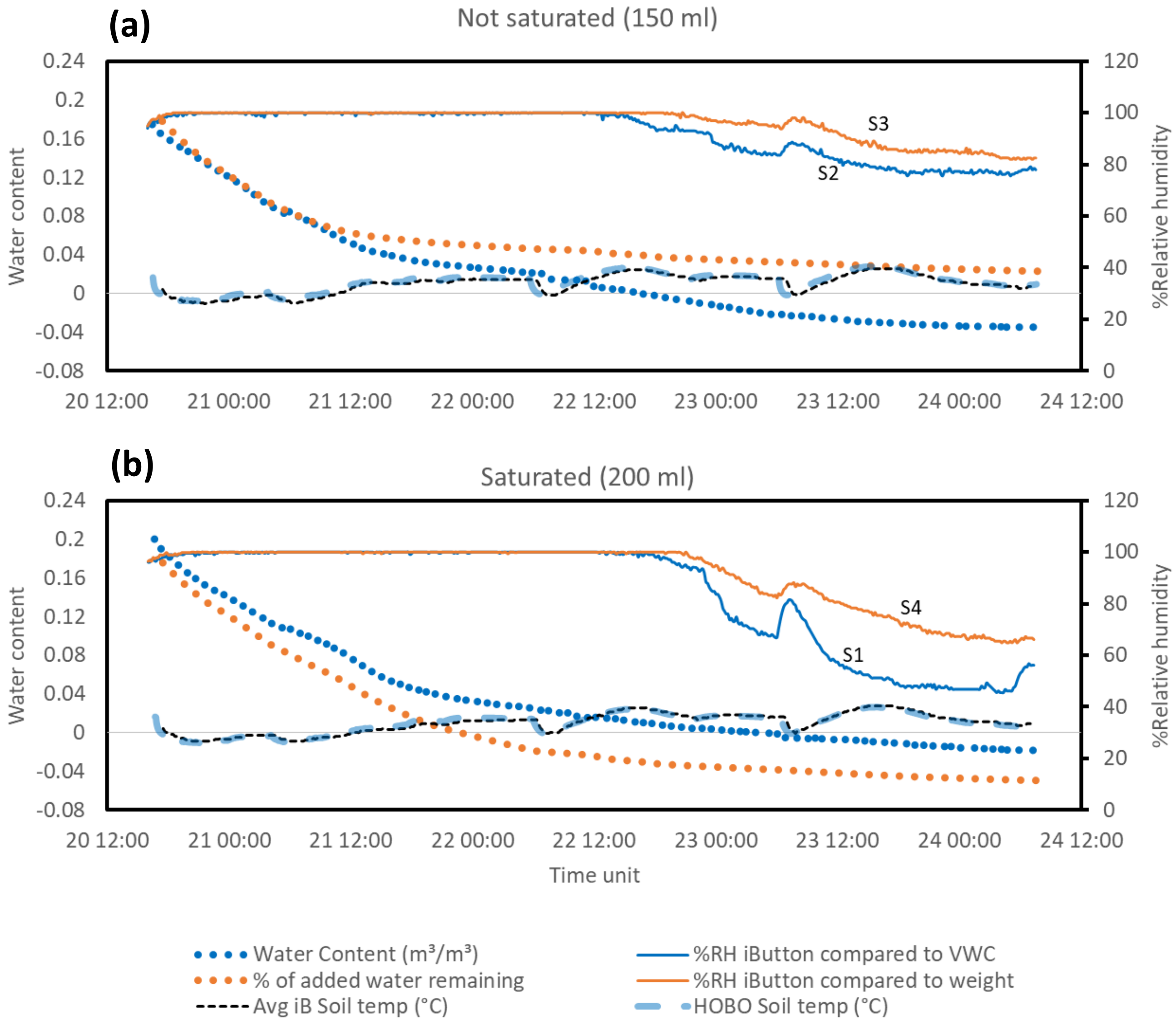

Figure 6. Experiment 1: The trends in RH, VWC and GWC for a soil container that is not saturated (a) and fully saturated (b) at the start of the experiment. Measurement commenced about 3 hours after wetting. In addition the soil temperature as measured with the EC5's associated soil temperature probe, as well as the average soil temperature as measured with the two iButtons used in each treatment is given.

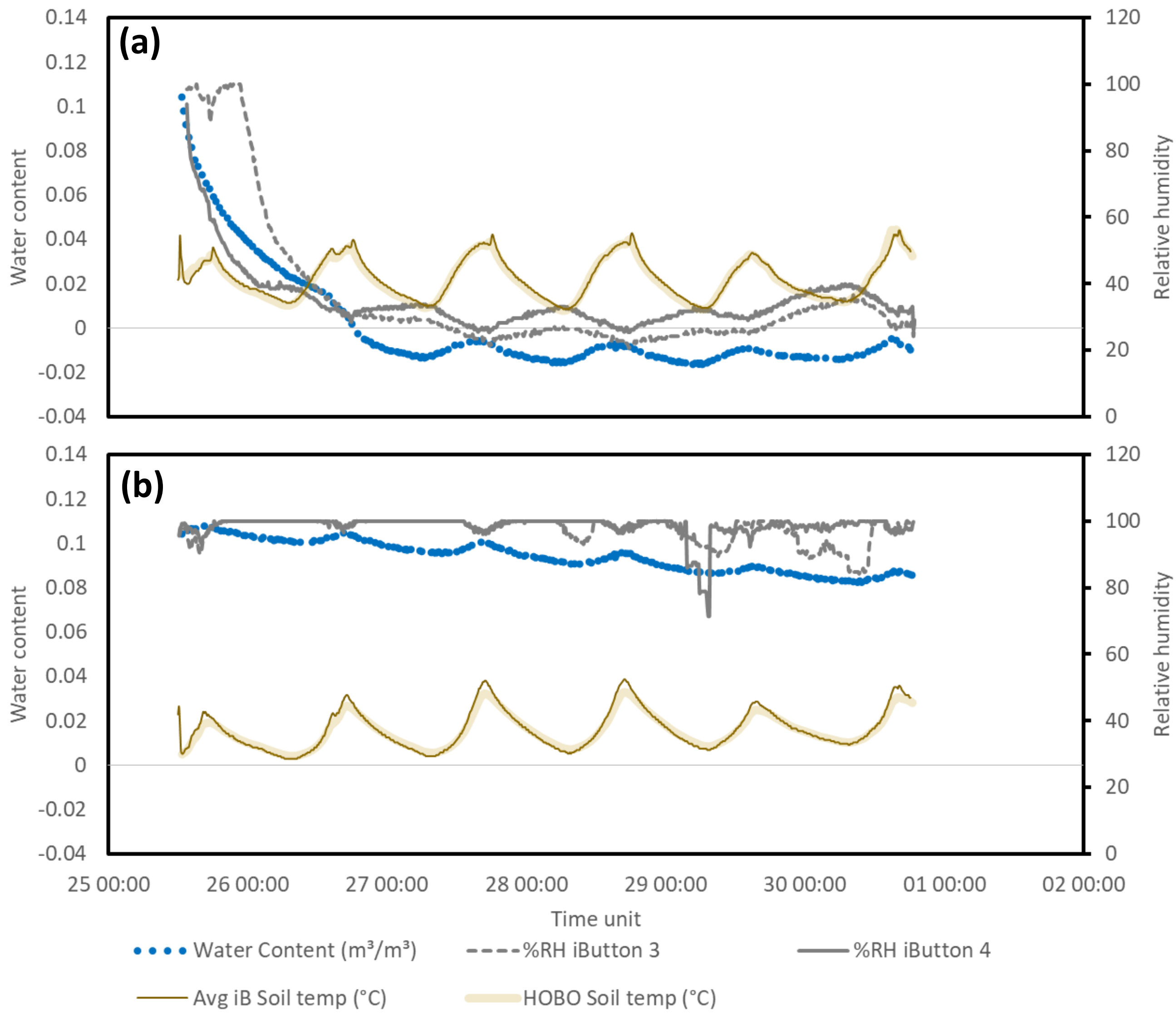

Figure 7. Experiment 2: The trends in soil moisture in terms of VWC (blue dotted lines, measured with an EC5) and % RH as measured using two iButtons per treatment, clearly reflected the two treatments, namely dry soil (a) and wet soil (b). The high values at the start of the experiment in (a) is the result of having to wet a small portion of soil to install the sensors. Also shown is the soil temperature as measured using the temperature sensor that was set up with the EC5 and an average across the two iButtons per treatment.

Discussion

The immediate conclusion from our results is that the iButtons, which measured the %RH of the air in the soil pore spaces, performed poorly compared to both the EC5 and gravimetric approach. The air in the soil pore spaces only dropped below 100% RH after at least 56% and 84% of the initial volume of water that I had added in respectively the non-saturated and saturated treatments was lost. In the in-situ experiment (wet treatment), both iButtons showed 100% RH for a long period before becoming highly variable without a clear a declining trend that reflected that of the VWC measured at the same time.

In addition, especially in the in-situ experiment, %RH clearly showed the influence of the soil temperature, decreasing when the temperature increased and vice versa. It is thus difficult to relate the RH value at any point accurately to the volume of water that is available for plant use, at least as long as the soil is relatively wet. The amount of variation between iButtons in both experiments was also curious, as I was convinced that the conditions inside the soil containers were much closer than the differences in %RH would suggest (see e.g. Figure 6a). However, these could simply have been caused by poor mixing of soil and sand or small pockets of clay material that affected water availability differently. In experiment 1 the RH as measured by both iButtons in the wetter sand started declining at least two hours later than the non-saturated treatment but dropped much lower. This is somewhat anomalous but could again be explained as poor sample preparation or differential effects of the fans.

Some of the problems I experienced echoed those of Fawcett et al. (2019), who also struggled to get good results in very wet soil conditions and failed to obtain a correlation of soil RH with VWC. In contrast, Schagen et al. (2021) reported no problems (but apparently did not query the iButtons' ability to measure in soil) and Wang et al. (2015) only pointed out that there is a need to measure ambient RH simultaneously with litter RH, to be able to correct for the effect of ambient conditions. The latter study was however conducted with the iButtons in contact with the atmosphere and is thus not directly comparable.

Despite these problems though, which were expected from the start, the study produced some unexpectedly good results. First, I did not have the equipment to dry out the soil samples to the levels that a desert plant would experience. I therefore expected to be measuring RH value over 90% for the duration of the experiment and was pleasantly surprised when the levels in all iButtons started dropping, going as low as 46% in the one saturated sample in Experiment 1. Notwithstanding the cyclical blips in RH in response to temperature, the trend was clearly downwards and echoed that of the VWC. The best result was the very similar patterns in the RH and VWC in the dry soil treatment in Experiment 2. Although this soil was probably still relatively wet compared to proper desert soils, this treatment came much closer to representing the conditions we are likely to experience in the field in the arid zone and is indeed one of the main reasons why I tested iButtons.

iButtons have several potential and real advantages over other methods. First, their small size means that they can be deployed relatively unobtrusively, avoiding problems with vandalism and theft. They are also relatively inexpensive, even when compared to the cheaper versions of the capacitance type of devices. Finally, they contain an integrated data logger capable of storing 8192 8-bit readings or 4096 16-bit readings with user-set measurement intervals. This translates to about 170 days of 2-hour measurement intervals (Analog Devices, Inc; Undated). Its temperature accuracy of ±0.5°C from -10°C to

+65°C and humidity resolution of 0.6% RH (Analog Devices, Inc; Undated) falls well within the resolution that is useful for ecological studies. Despite the apparent problems with the iButtons when trying characterize soil moisture, their advantages theoretically make them a viable option for distributed sampling over ecologically meaningful periods and spatial scales. At the very least it requires careful investigation to evaluate potential solutions for their apparent weaknesses.

Conclusion/Implications

The experiment showed that despite the iButton's reported weaknesses, they are capable of detecting trends in soil moisture that are similar to those measure by a capacitative sensor like the EC5, especially in dry soils. As the monitoring of soil moisture in restoration/rehabilitation applications in the arid zone will almost certainly encounter soil moisture levels well below permanent wilting point of 1.5MPa, a range where most capacitive sensors encounter problems. The current study's results were encouraging enough to conclude that it must be repeated at larger scale, with more replications, using more types of sensors for control and in more controlled conditions and different substrate types.

Relative humidity is a physical parameter with well-known controls. As such it should be possible to devise ways in which the combination of temperature and RH can be used to obtain a more accurate estimate of plant-available moisture in a range of substrates.

Recommendations

A sub-proposal for an expanded version of this study should be included in the proposal for Phase 2. The experimental design for that proposal should be an expanded version of the one used in the current report, with a laboratory-based phase followed by one or two field phases depending on the availability of testing sites. The factors that should be investigated are:

1. Prompted by the differences found in the current experiment, the precision of measurements among different iButtons should be investigated to determine whether the current results were due to substrate differences (thus real differences in sensed RH of pore spaces) or differences between the iButtons themselves, either the sensors or the custom-made housing.
2. The relationship between VWC and GWC must be established across a longer period (at least two seasons) and with different substrate textures , to determine the validity of using VWC as a control trend.
3. Systematic investigation of the differences between substrate texture in the RH of pore spaces.
4. Determine the relationship between the shape and volume of the measurement space in front of the iButton and the real and perceived RH in pore spaces and the potential for improvement of the holder's design.
5. Determine the potential for using a dry air injection into the measurement volume of the iButton holder at short intervals to overcome the problem of saturated pore spaces at the wetter end of the spectrum.

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