Insights into soil water use through interpreting moisture sensor data

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Abstract: Data interpretation is a major challenge given the increasing number of wireless soil moisture sensor networks. Although sometimes ignored, site-specific information like topography, morphology, and soil type are key to understanding soil moisture behavior. To improve our understanding of soil moisture sensor behavior, we evaluated three sites that were constituents of a 12 node wireless network deployed across a 37 ha field in locations selected for their geographic diversity. Each site had previously been characterized with a detailed soil profile analysis. Continuously monitored water content sensors were installed at 5 depths at 30 cm spacing starting at 30 cm. Site-specific characteristics significantly affected soil water dynamics. A hardpan in the soil explained unexpected differences in soil water with depth at one site, while low landscape position along with subsurface drainage explained another. Diurnal redistribution of water could also be seen at a third location down to 150 cm. Combining data from intensely monitored sites with plant type, topography, and soil morphology greatly improve our interpretation of soil moisture data in the field.

Key Words : soil moisture, water content, data analysis, soil water use

1. Introduction

Soil water content varies considerably over space and time. One of the current challenges in soils research is to quantify those differences at large scales and apply them to understanding watershed hydrology, ground water contamination, and plant water availability and use (Robinson et al., 2008; Vereecken et al., 2008). New inexpensive soil water volumetric water content (VWC) sensors make such ubiquitous measurements possible, but do not solve the problem of large amounts of data that require interpretation. Correlating typical sensor responses in the field to site knowledge is crucial to the success of these large-scale projects.

Studies have already tested the accuracy and repeatability of soil moisture sensors (Bogena et al., 2009; Kizito et al., 2008) as well as their viability in distributed wireless networks (Robinson et al., 2008). The sheer availability of the sensors, as well as the simple application of a distributed network can easily lead to large amounts of data that must be archived, displayed and evaluated. Inherent to these datasets will be three kinds of phenomena that must be dealt with correctly for proper interpretation: real data whose trends match the expectations of site, real data whose trends go against the expectation of the site but represent fragments of unexpected information about the system, and artifacts, such as temperature dependence and sensor failure, that should be filtered from the data. The objective of this note is to provide some perspectives on soil moisture measurement by discussing typical soil moisture data as a learning and evaluation tool for future monitoring projects.

2. Background

The Cook Experimental Farm at Washington State University is a 37 ha research farm which serves to study many aspects of no-till crop production. Started in 1999, the rain-fed farm grows a rotation of crops, divided between three major sections of the Farm. Precipitation averages 510 mm annually, with the greater portion occurring in the winter and spring. Soils on the farm are Mollisols (Palouse (Ultic Haploxerol), Naff (Typic Argixeroll), and Thatuna (Oxyaquic Argixeroll)) with argillic horizons and hard pans in some locations. The terrain is moderately hilly with low-lying areas receiving considerable runoff.

A study is underway to better understand spatially distributed soil water and evaluate the relationship between soil moisture dynamics and morphological features. To that end, 12 wireless nodes were installed at various points in the fields using a stratified random procedure to ensure variability and sufficient distance between sensor locations (Fig. 1). At each site we buried VWC, temperature, and electrical conductivity (EC) sensors (ECH$_2$O-TE and 5TE, Decagon Devices, Inc., Pullman, WA) at 30 cm increments

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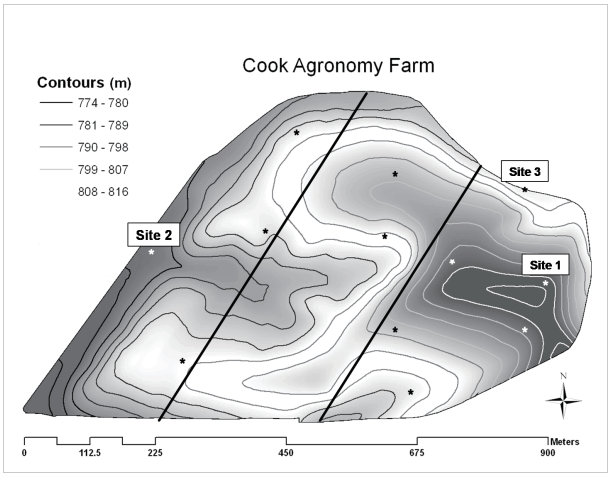

Fig. 1 Cook Experiment Farm at Washington State University. This study focuses on three sites (marked Site 1, 2, and 3); a subset of the 12 measurements sites (stars) in the project. Contour lines and shading indicate possible drainage paths for water toward Site 2.

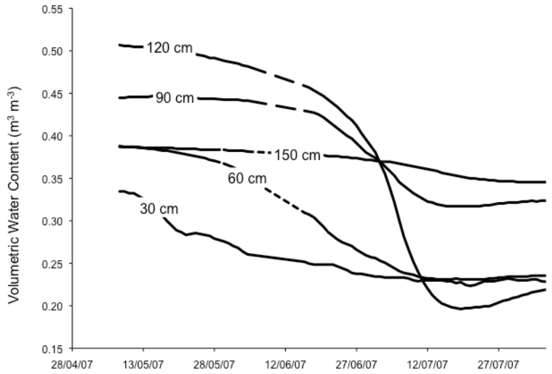

Fig. 2 Changes in VWC with time at Site 1. The sensor at 120 cm, located just above a hardpan layer in the soil, shows the largest change over the summer dry-down period.

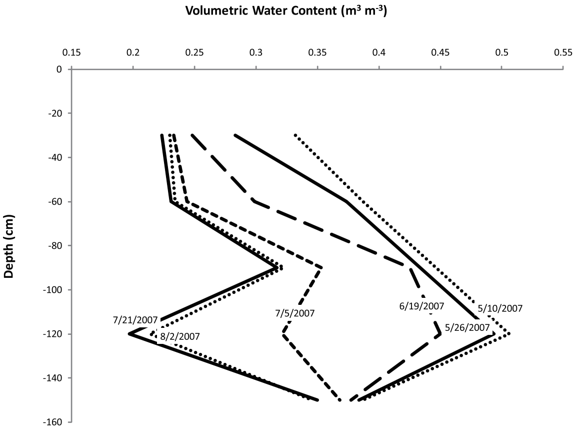

Fig. 3 Changes in VWC with depth (convention: negative values indicate depths below soil surface) for the same time period at Site 1.

from 30 to 150 cm below the surface. The sensor nearest the surface was installed into the sidewall of a 45 cm deep trench; the other four sensors were installed in the base of a 5 cm auger hole at their appropriate depth (one per hole) and backfilled and repacked with native soil (with care to limit air gaps).

Soil moisture, temperature, and electrical conductivity data were collected continuously at 1 hour increments (Em50 Datalogger, Decagon Devices, Inc.) and transferred via a central collection point (DataStation, Decagon Devices, Inc. and CR850, Campbell Scientific, Inc, Logan, UT) and cell modem gateway (AirLink, Campbell Scientific, Inc.) to the internet. Gaps in data were generated from regular infield operations (spraying, fertilizing, etc.) as well as harvest when the data collection systems were removed from the field. General environmental data, such as precipitation, were collected at a central location in the field. Slope, aspect, elevation, and morphology were measured directly at each of the 12 sites.

In our analysis, we consider three of the sites in depth to learn more about sensor behavior. The first site was located near a hilltop with a southerly exposure and was planted with winter wheat (Triticum aestivum) the preceding fall. Augering for sensor installation unearthed a hardpan layer between the 120 and 150 cm sensors. The location of Site 2 was at the bottom of a large drainage area (Fig. 1) where a robust crop of triticale (*Triticale* hexaploide) was growing; no soil anomalies were exposed in this location. Also planted to winter wheat, the third site was located on a toe slope and was more typical of the other nine sites in the study.

3. Data Interpretation and Discussion

Water use by the winter wheat at Site 1 over the summer of 2007 was similar to what we expected for the silt loam soil where they were installed (Fig. 2). Rain fed wheat is known to root deeply in the soil and Fig. 2 shows the continuous progress of the root extraction down through the soil to 1.2 m deep. Curiously, the 120 cm sensor read much higher than the other four at the time of installation. Further, the initial reading of 0.50 m^3 m^{-3} is certainly near the upper limit for the silt loam soils of the Cook Farm. Although several things might have caused this (poor installation, low-density soil, and air gaps around the sensor), during installation we observed a hardpan between 120 and 150 cm that may be the root cause. It is likely that infiltrating water ponds above the hardpan and keeps the soil closer to saturation compared to other depths.

Moisture content change with depth due to crop water use is also somewhat unexpected (Fig. 3). Water is taken from the 30 and 60 cm levels as expected; as the 30 cm sensor reached a minimum, the 60 cm sensor begins to drop in earnest. Initially, moisture at 90 cm shows a similar trend, but does not drop as low as those at 30, 60, or 120 cm. The reason for this is unclear. At the same time, the water content at 120 cm is dropping quickly, showing a higher preference for water at that depth compared to 90 cm, possible because of the abundant water above the hardpan. The 150 cm sensor exhibits very little change across the entire sum-

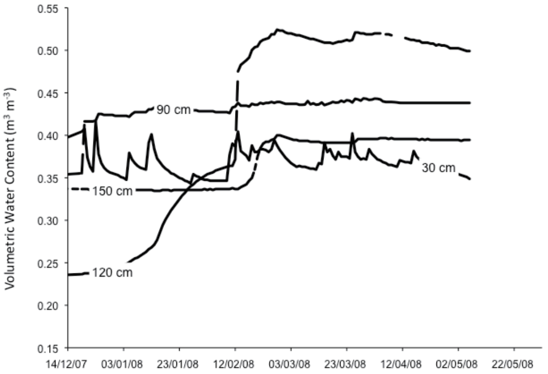

Fig. 4 Winter recharge at four depths (60 cm sensor was disconnected) at Site 1. Precipitation events are visible at the 30 cm sensor, while recharge at deeper depths occurs much more slowly. The soil surface was devoid of living plants until after 1/4/08.

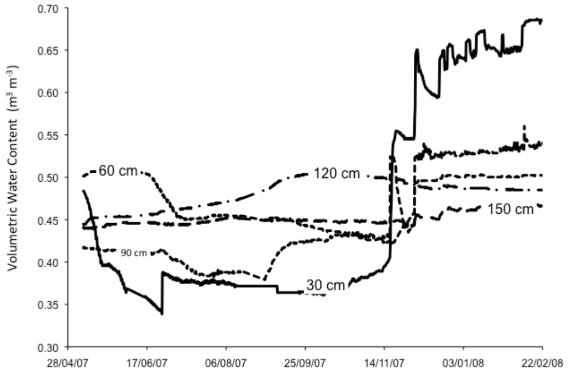

Fig. 5 Summer water use at the low-land site (2). After an initial response to plant use, sensors show water content remains relatively constant or increases across the summer.

mer. Although this is reasonably deep in the soil, most of the other sites growing wheat exhibited as much water use at 150 cm as at the other measurement depths. Although there are other possible reasons, it is likely that the hardpan not only impeded water movement, but also limited root growth below that level, thus reducing water uptake (Passioura, 2002).

The winter recharge period in Fig. 4 shows soil moisture returning to similar VWC levels as the previous year. As expected, infiltration events can be seen clearly at 30 cm, but produce only small changes at 90 cm (60 cm sensor was disconnected). Over time, the upper soil layers exceed field capacity and drain water down to the 120 cm and finally 150 cm levels. All sensors returned to VWC values similar to their previous spring values giving confidence that changes observed are related to soil processes and not ancillary effects.

Site 2 requires more interpretation (Fig. 5). Without knowledge of its landscape position, the reaction of all the sensors would be perplexing. At 30 and 60 cm, the water content initially decreases similar to Site 1, but flatten after a rainstorm. Sensors lower in the profile show water content that increases at times during the season. Although some of the difference in water uptake could be attributed to a change in crop type (triticale vs. wheat), the vitality of the crop throughout the summer (personal observation) indicated it had adequate water. The gradual increase at 90 and 120 cm indicate water was coming from somewhere other than the soil surface as there was no change in the sensors above them. Interestingly, the 150 cm sensor does not respond in a similar manner suggesting water may flow more easily in some layers of the soil than others. These data may be consistent with information gathered at Site 1 where water was shown to pond at certain depths in the soil and have poor connectivity to lower regions.

Often it is difficult to tell the difference between a functional soil sensor and one giving meaningless data. The 30 cm sensor at Site 2 (Fig. 5.) appears to be malfunctioning at the beginning of 2008. After two rain events in late fall, data increases beyond 70 % and becomes erratic, with drops that cannot be explained in soil environment. Although there may be physical explanations for this (freeze/thaw, air voids created around the sensor by fauna), a more likely explanation is a problem in the sensor itself. This sensor still performed as expected during the next year (data not shown) suggesting the failure is intermittent.

Several studies have shown soil moisture data that contains a superimposed temperature signal of up to 0.003 m^3

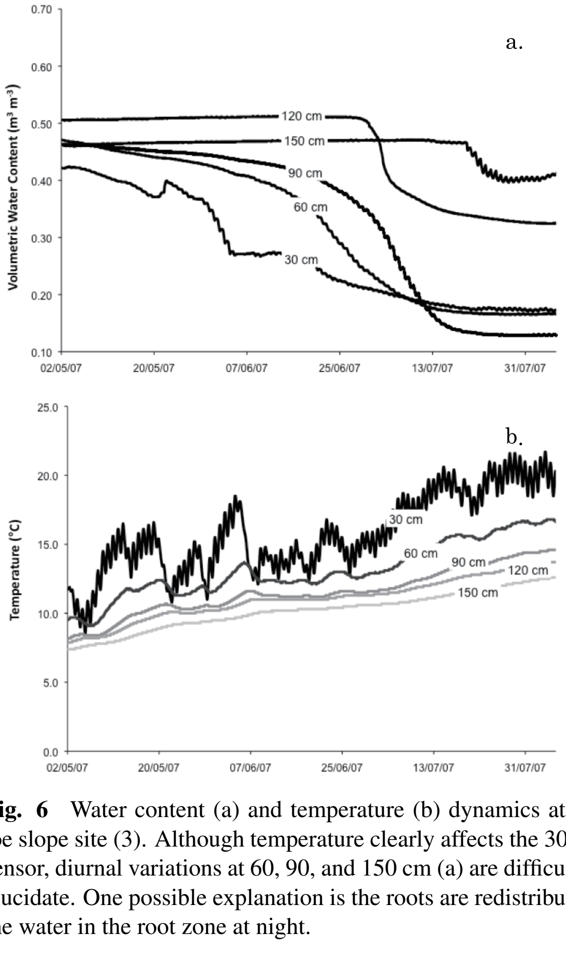

Fig. 6 Water content (a) and temperature (b) dynamics at the toe slope site (3). Although temperature clearly affects the 30 cm sensor, diurnal variations at 60, 90, and 150 cm (a) are difficult to elucidate. One possible explanation is the roots are redistributing the water in the root zone at night.

m^{-3} /°C or more (McMichael and Lascano, 2003; Or and Wraith, 1999). Although most sites did not exhibit this behavior, it can be seen in Site 3 at all but the 120 cm depth at various times during the summer (Fig. 6a). Our initial reaction was to attribute it to temperature affects on the measured dielectric. However, Figure 6b shows little or no diurnal temperature change beyond the 30 cm sensor. This, coupled with the fact that the fluctuations can only be seen once VWC begins to decrease (i.e. root water uptake from that depth), suggest redistribution of water by plant roots as a possible explanation for the phenomenon.

4. Summary

Large amounts of data that require intensive processing are a result of new inexpensive sensors and more sophisticated dataloggers. Although the opportunity for more intensive sampling can lead to better understanding of the natural environment, correct data interpretation of these data is a necessary precursor. Our review of data from the Cook Experiment Farm shows soil moisture often does not trend in the manner we expect. Things like landscape position, soil morphology, and plant response change water content data in ways that would not be expected by simply looking at precipitation data or soil surface features. Successful analysis of these characteristics can lead to higher quality data analysis and a better understanding of how water behaves in the soil.

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要 旨

ワイヤレス土壌水分センサーネットワークの数が増加してくると，そのデータ解釈が主要な課題となってくる．土壌水分の特性を理解するためには，現状では無視されている地形，形態，土の種類などの現場特有の情報が重要となる．現場の条件に応じた土壌水分センサーの特性を理解するため，我々は地形が異なる区域内にある 37 ha の圃場の 3 つのサイトを評価した．これらのサイトには 12 個のノードを持つワイヤレスネットワークが配備されている．各サイトでは事前に詳細な土壌断面調査が行われている．連続測定する土壌水分センサーを深さ 30 cm から 30 cm 間隔で 5 深度に埋設した．観測の結果，現場特有の特徴が土壌水分の動きに大きく影響を与えることがわかった．サイト 1 では深さ方向に対する想定外の土壌水分の違いを土壌中の硬盤により説明できたが，サイト 2 では地下排水を伴う低地によって説明できた．サイト 3 では，150 cm の深さまで水分の日変動が見られた．集中観測地点のデータと植生，地形，土壌形態を合わせることにより，圃場における土壌水分データの解釈が飛躍的に向上する．

キーワード：土壌水分，含水率，データ解析，土壌水分利用