SOIL WATER AND PLANT CANOPY SENSOR TECHNOLOGIES TO OPTIMIZE WATER AND NUTRIENT USE

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ABSTRACT

In many respects, agricultural technology is doing things now that were only imagined 20 to 30 years ago. Yet, grower tools that provide information and actionable knowledge on water and nutrient availability still remain a challenge. Clearly, rapid development of data transfer and processing platforms to date has provided rich maps of grower fields with overlays of location-specific information but their utility is still limited by our ability to accurately measure the parameters that are the foundation of this knowledge. To supply enough water and nutrients to crops, growers must know how much water is available and how that availability will change with depletion. Currently, systems only tell half the story. This presentation will focus on the emerging opportunity of combining robust soil water content and water potential measurements in the field to get a complete picture of soil hydraulic properties and behavior. And, along with electrical conductivity and plant surface reflectance indices, how it is possible to use this information to optimize water and nutrient use. Indeed, with these data, it may even be possible to lighten the grower decision-making burden by using machine learning. We will briefly explore these opportunities and what's necessary to get there.

INTRODUCTION

Agricultural technology is doing things now that were only imagined 20 to 30 years ago, yet grower tools that provide information and actionable knowledge on water and nutrient availability still remain a challenge. Rapid development of data transfer and processing platforms to date have provided rich maps of grower fields with overlays of location-specific information, but their utility is still limited by our ability to accurately measure the parameters that are the foundation of this knowledge.

To supply enough water and nutrients to crops, growers must know how much water is available and how that availability will change with depletion. Current systems only tell half the story. This talk will focus on the emerging opportunity of combining robust soil water content and water potential measurements in the field to get a complete picture of soil hydraulic properties and behavior—and, along with electrical conductivity and plant surface reflectance indices, how it is possible to use this information to optimize water and nutrient use. Indeed, with these data, it may even be possible to lighten the grower decision-making burden by using machine learning. We will briefly explore these opportunities and what's necessary to get there.

Improving Agricultural Sustainability

Agriculture sits at the nexus of many important issues that have risen to the forefront of the public consciousness. Dwindling supplies of freshwater threaten communities. Nations and agriculture worldwide are under intense scrutiny because of disproportionally high use of this resource. Use of conventional fertilizers depletes fossil fuels and pollutes downstream watersheds, aquifers, and estuaries, while pesticides and herbicides applications push ecosystems out of natural balance. Additionally, damage to soil as a key ecosystem service threatens our ability to produce food and other products for an ever-increasing population.

With all these storms brewing on the agricultural horizon, it is not surprising that there is a sudden surge of proposed solutions. While many of these appear promising, they chiefly rely on software-based innovations to improve user interfaces and predictive modeling of outcomes but fall short of introducing real jumps in technology to better quantify the soil and micro-climactic environment. This is significant as progress on these model-based knowledge systems depend completely on our ability to input relevant and accurate data as any information they can provide will only be as good as the data they use as inputs. Thus, there is an urgent need to not only develop sensors and instruments that make relevant measurements, but also to combine them together to provide our expertise as a science community to those who are charged with feeding the world.

Those who grow crops for a living are faced with a challenge. While it is unlikely that there is a widespread lack of concern for the environment, revenue is generated through yield and quality. Thus, in the absence of adequate decision support tools, a grower’s choice of irrigation amount, frequency, fertilizer use, and soil management can fall to what is most expedient. It is often said that to over-irrigate receives a slap on the hand, while to under-irrigate will cost you your job. Clearly, without insight into root zone water use and requirements, it is in the grower’s best interest to maintain soil water well above any critical limits. Although not identical, nutrient management faces very similar challenges. To make progress, science must address this gap in measurement knowledge through a holistic approach to understanding the movement of water and nutrients in the soil-plant-atmosphere continuum.

Integration of All Three Areas is Key

Data suggest that the vast majority of irrigation scheduling is based on replenishing lost plant water through evapotranspiration (ET) estimation. Campbell and Campbell (1992) opined that this is similar to a restaurant waiter knowing when to stop refilling water glasses by the look on the patron’s face; it fails to address directly how much is needed. ET is still valuable when assessing plant water needs; we just need more. Soil moisture monitoring, which makes up a small but growing portion of the irrigation scheduling market, provides information about how much water is available to the plant, but is often ambiguous about critical limits for plants (which we’ll get to in a moment). Plant-based measurements have to make up the other leg of the three-legged stool. Despite being used for decades in irrigation management, the technology really hadn’t advanced beyond the reliable but labor-intensive pressure chamber until visible, infrared, and thermal radiometry started gaining popularity in the early 1990s. Today, satellite, drone, or tower-based remote sensing of things like normalized difference vegetation index (NDVI), photochemical reflectance index (PRI), and canopy temperature are delivering important information on crop health. Still, as a stand-alone assessment, these techniques also lack the interpretive power to independently guide decision-making.

Uniting Soil Moisture into a Complete Hydrological Picture

Plants take up water from the soil along a potential gradient that pulls water from the soil, through the plant, out through the stomates, and into the very dry atmosphere. For the plant to access water, the soil has to remain within critical water potential limits to allow that water to be available for uptake (Dane et al. 2006). This knowledge was the force behind considerable irrigation research during the 1950s and 60s to determine optimal water potential (WP) for growth. Despite a wealth of publications, this knowledge has largely fallen from the scientific consciousness due to the challenges of making such measurements. The discovery of dielectric-based measurements in the mid-1970s changed much of the soil moisture effort to assessing water content, a simpler, less expensive, and possibly more understandable parameter. In the intervening years, technological advances have improved the cost, reliability, accuracy, and usability of these sensors to a point that this technology is fairly mature today (although challenges related to measurement volume remain). Yet, soil water content alone cannot provide actionable information about plant available water.

Soil water content is a percentage-based measurement of how much water is in the soil on a gravimetric or volumetric (VWC) basis. All *in situ* measurements are volumetric and require calibration to the gravimetric, oven drying-based standard. The change in soil water content over time indicates how much water has been lost and, in the case of irrigation, how much is required to replace it. A simple example may help illustrate this. If a 1 meter deep soil changes from 20% to 15% water content (by volume, 0.05 m^3 of water lost from 1 m^3 of soil), it will require 5 cm of rain or irrigation water (0.05 m x 1 m x 1 m volume) to replenish water loss. Thus, water content supplies vital information for the irrigator. But, in this example, it is not clear when and if the water should be replaced. In a sand, 15% VWC is an upper limit for water to avoid drainage. In a clay, 20% VWC is below the permanent wilting point. Regardless, it would take someone with expertise to assess the soil and set the limits.

Combining water potential and water content sensors in the soil has the possibility to eliminate this difficulty. The relation between the two is called the soil moisture release curve (MRC) and can be used to determine the soil type (Crawford et al., 1995), unsaturated hydraulic conductivity (Rieu and Sposito, 1991), and limits of plant available water. Interestingly, only one paper published so far has attempted to generate this relationship *in situ* (almost all are done in the lab), and even this effort covered a fraction of the total plant available range (Jabro et al. 2009). This is likely due to the aforementioned challenges involved with *in situ* water potential measurement. Recent advances in robust, accurate, and maintenance-free WP sensors has opened an opportunity to evaluate whether it’s possible to create MRCs in the soil.

Riding the Wave of Spectral Understanding

Emerging technology has also changed opportunities for using spectral indices to assess plant health (Taghvaeian et al. 2013). Although countless studies have shown the link between spectral reflectance or emission and plant health, it has only been in the last several years that those measurements were affordable. These new sensors allow the continuous, meteorological stand-mounted monitoring of canopy greenness (NDVI), xanthophyll non-photosynthetic quenching (PRI), and infrared canopy temperature (Infrared Thermometer, IRT). Indicators of plant health have the potential of adding to our knowledge of critical availability in the soil as well as nutrient deficiencies and pest pressure. What remains to be seen is whether these indicators are pronounced enough and if they offer any opportunities for early detection.

Combined with measurements of electrical conductivity in the soil, it also may be possible to spot nutrient deficiency.

MATERIALS AND METHODS

A turf grass example will show how these concepts are combined to improve irrigation and avoid nutrient loss through drainage. A full description of the experimental setup can be found in Campbell et al. (2017), but some details will be given here for context. The experimental site was located at the Experimental Research Center adjacent to the Brigham Young University campus. There, two large turf grass plots provide experimental information on the performance of stadium turf (north plot) and urban landscape (south plot). Each plot was established using engineered soil according to Table 1. The sites were instrumented to improve irrigation scheduling and to provide early warning when irrigation systems failed. Soil water content and matric potential sensors were collocated at two depths (6 and 15 cm) with a single water content sensor at 30 cm at two locations in each plot (four total locations). A typical micro-meteorological station gathered weather data at the site and NDVI and PRI sensors measured plot surface reflectance continuously. The plots were irrigated by an automated system that ran on a timer but could be controlled manually to optimize irrigation.

Table 1. Soil sand, silt, and clay percentages for engineered soil in turf grass plot along with texture classification.

Location	%Sand	%Clay	%Silt	Texture Classification
South turf plot	**77.7**	**9.6**	**12.7**	**Sandy Loam**
North turf plot	**96.7**	**1.6**	**1.7**	**Sand**

RESULTS AND DISCUSSION

Although the system has collected more than two years of data to date, the summer of 2015 illustrates the behavior of soil moisture and plant performance based on irrigation frequency. Figure 1 shows the trends in matric potential and water content from June to October in 2015. Of particular interest are three periods representing differing irrigation approaches. The first period, during June and early July, irrigation was based on the calendar only and water was applied at regular intervals. The second period, constituting late July and early August, allowed the soil to dry to a fixed soil moisture, then watered to refill the profile. And the last period, from mid-August to the end of September, allowed the soil to dry until the daily change of VWC in the root zone ceased.

The effective rooting depth of the turfgrass was from 0 to 15 cm and dynamics at the 6 and 15 cm sensors are assumed to be water reaching (when increasing) or taken up by (when decreasing) roots. Water content at 30 cm show the larger irrigation events. Although we cannot predict the actual deep drainage loss, increases in water content at 30 cm are assumed to indicate applied water infiltrated past the roots and did not benefit turf growth, therefore constitutes a waste of water resources.

The fixed drying periods shows daily trends in both water content and, as the soil dries, matric potential. Here, diurnal changes in water content are clearly visible at 6 cm and, although muted, at 15 cm. These data inform our understanding of critical ranges for plant water uptake by showing the soil moisture as VWC increases at 30 cm (July 14th) after the July 13th irrigation but the subsequent irrigation that refilled the root zone (6 cm MP at -9 kPa) with little visible change at the 30 cm sensor.

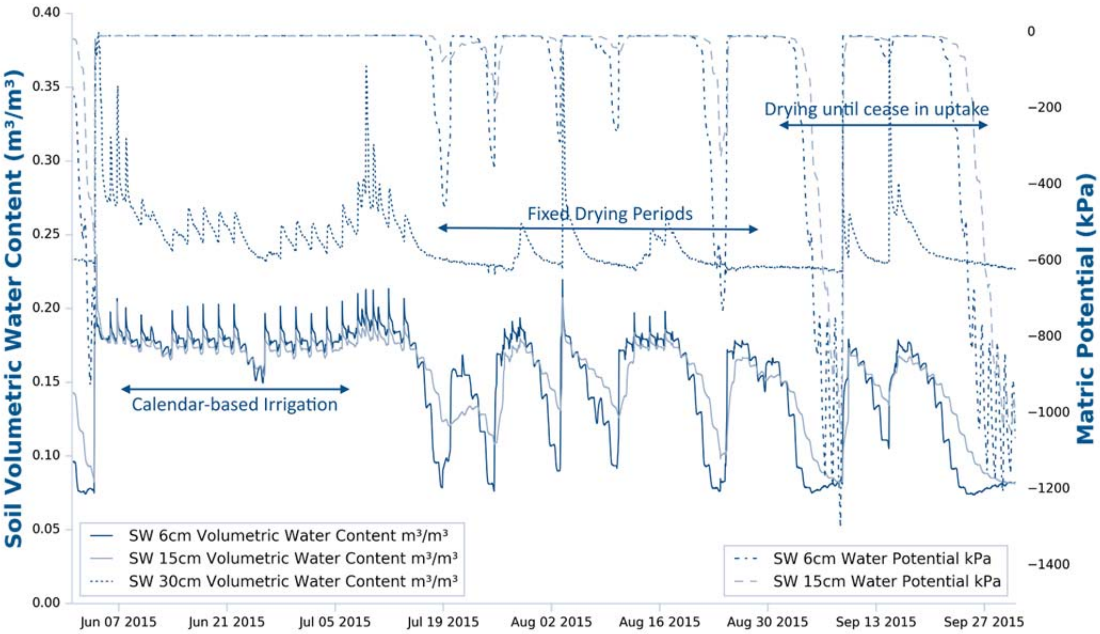

Figure 1. Time series of water content and matric potential at different depths in the turfgrass root zone during the summer of 2015. Three distinct irrigation regimes are called out including calendar-based irrigation during June, fixed drying periods during late July and August, and drying until cessation of water uptake in September. Changes in 30 cm VWC are indicative of water moving beyond the root zone.

The "Drying until cease in uptake" time series shows *Poa pratensis* stressed into dormancy (Fig. 2) as soil moisture starts at the upper optimum level and decreases until soil water uptake ceases at 6 cm (Sept. 4). Matching 6 cm matric potential with this time provides a minimum water potential limit of approximately -500 kPa. Although water is still being extracted from the volume measured by the 15 cm VWC sensor on the same day, it reaches a similar level two days later, with comparable level of matric potential as well. Still, this is probably not the lower optimum as minimal or no water uptake in the root zone suggests plants have entered a stressed condition, and the quality of the turfgrass stand will be affected. Yet, the previous day shows a modest water uptake at a matric potential of around -300 kPa, which could be used as a lower optimal limit.

Ideally, other indicators of stress like spectral reflectance (SR) could be used with soil moisture measurements (Taghvaeian et al, 2013). Results from the turfgrass (Fig. 3) show that SR did broadly indicate some correlative effects. In general, we would expect NDVI to increase with plant vigor and canopy closure as chlorophyll absorbs more red light and reflects more infrared while leaves senesce and show the opposite effect under stress. Trends in the NDVI (Fig. 3a) do follow this expectation, but unfortunately, without arrow prompts in the graph, they would be far from intuitive, possibly even overshadowed by seasonal phenological trends. Indeed, noise in the day to day data makes it very difficult to come to any conclusion on how the well-watered or stress condition may be affecting the reflectance, limiting or negating the value of a NDVI-based stress measurement. Something similar can be said of the PRI data (Fig. 3b). Photochemical Reflectance should indicate a plants readiness to absorb and utilize solar radiation. The upward trend in PRI during the well-watered period may indicate that the turfgrass is growing, creating more chlorophyll, and better able to absorb and utilize radiation using its chlorophyll, not shunting it off to the xanthophyll. During the fix-drying period, PRI decreased, but to levels similar to the initial value of the calendar-watering period, possibly indicating low amount of stress. And finally, the precipitous drop during the water-withholding period below either of the first two suggests a severe shortage of essential water for photosynthesis. However, like NDVI, trends at other times in the time-series show similar behavior with no good explanation. The reason for variability in the data is probably related to the radiation source for the sensor. Because they depend on solar radiation to measure reflectance, they are subject to all the errors associated solar zenith and azimuthal angle, variable cloud cover and type, and leaf angle distribution at the surface. And despite the considerable data filtering already done on the NDVI and PRI signals, and the sensor that normalized the reflectance to incoming radiation, it was still difficult to fully smooth the data.

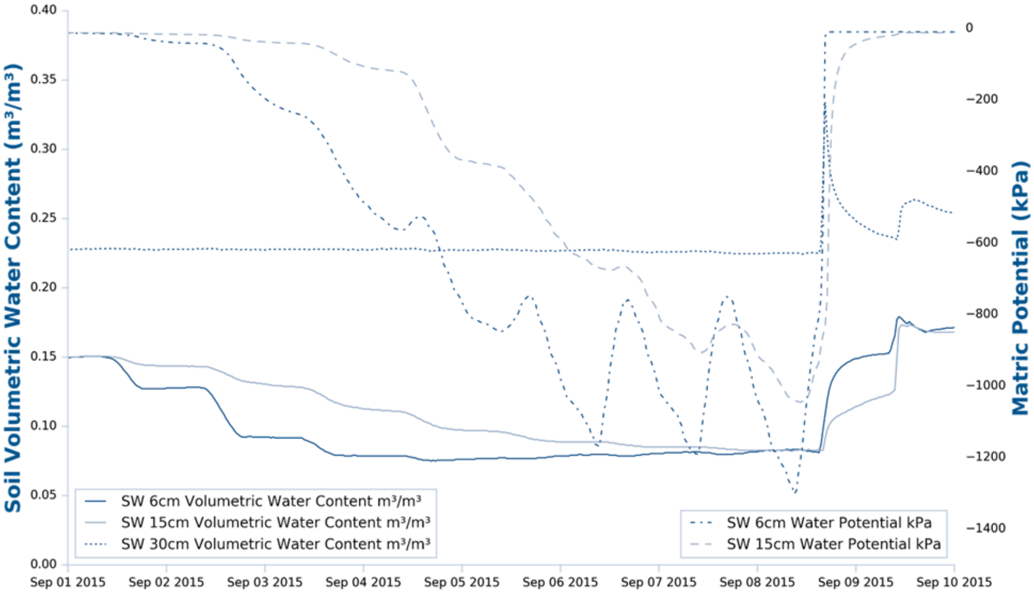

Figure 2. Soil water dynamics during a period of no irrigation where the soil dries until no water is taken up. Plant water uptake appears to stop at 6 cm and 15 cm depths in the turfgrass root zone at an approximate matric potential of -500 kPa. Continued changed in MP with no concomitant change in water content is indicative of the coarse texture of the soil, implying that nearly all of the total volume of water in the sand was removed when the soil was wet.

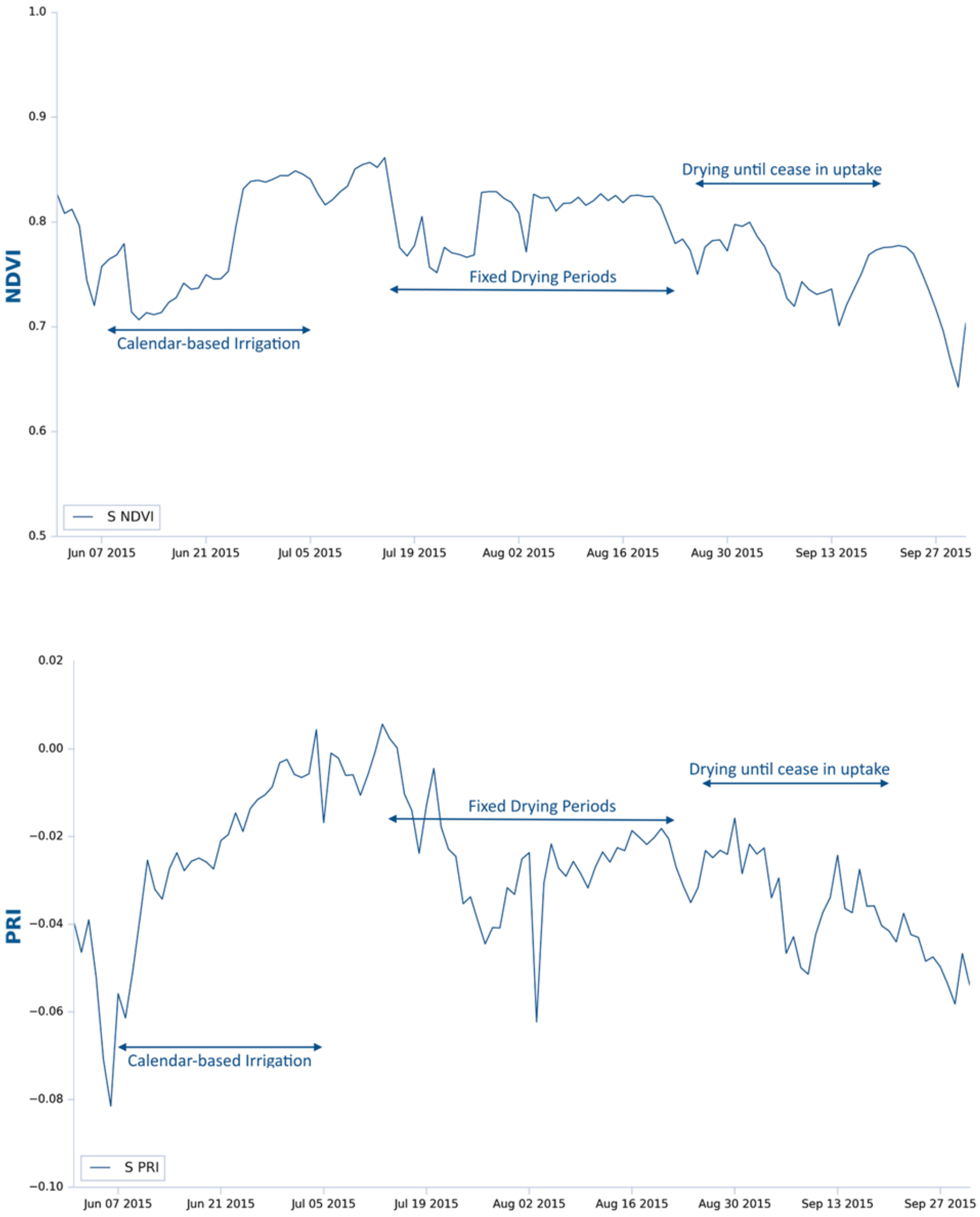

Figure 3. Spectral reflectance from the turf grass surface during the summer of 2015 is shown using a) Normalized Difference Vegetation Index (NDVI) and b) Photochemical Reflectance Index (PRI). Callouts show the change in reflectance during calendar irrigation and two water deficit periods.

SUMMARY

Sensors and their associated measurements play a foundational role in the future improvement of irrigation and nutrient management. Certainly, considerable work has been done to provide these data to growers, but because of technology limitations, much of the effort has focused on indirect assessments like evapotranspiration. Advances in materials, electronics, and science are quickly opening up new opportunities to sense the complete soil-plant-atmosphere continuum and we have the opportunity to combine these measurements together to provide knowledge products to grower. Correctly understood, these products move the responsibility for interpretation from the irrigator to the scientists who are collaborating in the development of a software user interface.

The short case presented above provides two examples of such measurements. Combining water content and matric potential sensors in the root zone helped provide a complete picture of water uptake and availability that was critical to determine the needs of the plant while preserving water in the root zone. Although water content seems to be the logical choice, it could only indicate that water was in the profile, how much was taken up, and if any was moving below the root zone. The matric potential provided a framework to understand the optimal range with which to irrigate the grass and a sanity check for whether there were other issues related to plant water uptake like low hydraulic conductivity in the soil. The spectral reflectance data was not as useful to the study. No clear indication of stress was visible until well after other soil and physiological indications. Still, these difficulties may lie in the sensors themselves instead of the approach. Because they used a passive light source (the sun), constantly varying conditions (solar angle, leaf shading, cloud cover, leaf angle distribution, water stress) made signal interpretation extremely difficult. If we used an active light source, these results may have been entirely different.

Agriculture and its associated disciplines have the opportunity to lead efforts towards environmental and economic sustainability by continuing to integrate technology that helps conserve natural resources like water, soil, and nutrients. We in the research field have the ability to aid this work by continuing to look for ways to integrate these tools and provide solutions to growers. Together, we can meet the needs of tomorrow.

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