Integrating Soil Moisture and
Other Sensors for Precision Irrigation

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Abstract. The use of sensors can provide quantitative information to help guide and automate the decision making process for irrigation. This paper provides an overview of the most common sensors that can be used for this purpose. Such sensors include those that are commonly used for weather stations as well as sensors that indicate the water needs of the crop. Irrigation demand can be determined directly from soil water measurements or indirectly from the water status of the crop. Pros and cons of these approaches are discussed.

Keywords. Evapotranspiration, Light, modeling, relative humidity, remote sensing, temperature, water, wind

Introduction

Sensing environmental conditions is becoming easier and cheaper, providing opportunities to integrate such sensors into irrigation systems. Good, quantitative information can be used to help guide decision making with regard to a) when to irrigate and b) how much water to apply. However, simply collecting data may not be useful, unless that data is presented in an actionable form; the data need to be converted into usable information. Thus, the software side is at least as important as the hardware. This paper focuses on available sensors for use in irrigation control systems, while other papers from this workshop discuss the hardware needed to measure and collect the data, software development to present the data in a user-friendly, actionable format, the use of sensor networks for irrigation management, and the economic impact wireless sensor networks can have.

There are different ways in which sensor data can be used to help make irrigation decisions. The simplest method is to turn irrigation on and of based on whether a particular sensor reading is below or above a particular threshold. For example, irrigation can be turned on and off based on the amount of water present in the soil or based a measure that is an indicator of plants stress. More complex approaches may involve the modeling of crop water use or evapotranspiration (ET, the total amount of water evaporating from the soil and transpired by the crop) based on weather conditions and crop factors.

Although there are many different ways to estimate ET from weather conditions, the most common approach is the FAO Penman-Monteith method, which uses commonly measured weather data to calculate a reference ET value (ET_0). The ET_0 is an estimate of the ET from an extensive surface of green grass with a height of 12 cm (about 5"). This ET_0 is than multiplied by a crop coefficient (K_c) to calculate the expected ET for a particular crop. Crop coefficients depend on the size of the crop, and thus change over time. Detailed information on K_c values is available for most agronomic crops and some horticultural crops. This approach is difficult to apply to landscapes with mixed plantings, because of the difficulty of determining an accurate K_c. Note that the resulting ET estimates assumes that the crop has access to unlimited water resources, and adjustments need to be made if water availability is limited by drought or salinity. Weather information needed for the FAO Penman-Monteith method include solar radiation, temperature, relative humidity, wind, and rain. The 'simplified' equation to estimate ET using the FAO Penman Monteith method is:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Why is this rather complicated equation considered a simplification? Because using this equation, we can estimate ET_o from just a few readily available measurements: temperature, radiation, wind speed, and relative humidity. This makes it possible to calculate ET_0 from standard weather station data. The units for ET_o are in mm/day, or can be converted to inches. For more details, see Allen et al (1998).

There is no general agreement whether it is better to control irrigation directly using sensor readings or based on model predictions of ET; different applications may require different solutions. ET modeling generally works well for large scale, agronomic crops or turf grass, but is more difficult to apply in landscapes with a large variety of plants or in situations where accurate K_c values may not be available. Another option is the combined use of sensors and models, where irrigation could be controlled using models, while sensors are used to assure the plants do receive adequate water (or vice versa).

Sensing Weather Conditions
Weather conditions play a large role in determining water use, and thus irrigation requirements, of crops. In many cases, weather data are available from nearby weather stations, in which case an on-site weather station may not be necessary. However, when using weather data from an off-site weather station, it is important to verify that the information from that station is actually applicable to the site of interest. Micro-climatic differences are common, and as a result, there can be significant differences in weather conditions among sites that are close

together. The one weather variable that is perhaps most different across relatively small distances is rainfall.

Light

Light, or solar radiation, is probably the most environmental variable affecting plant water use. There are two common ways to measure light that are relevant to plants a) the total energy of the incoming light (shortwave radiation) and b) photosynthetically active radiation. The difference between these two measures is that shortwave radiation includes near UV, visible, and near infra-red radiation, spanning radiation of wavelengths from approximately 200 to 3000 nm. These wavelengths span the entire spectrum of radiation coming from the sun and shortwave radiation measurements thus determine the total energy flux of the incoming sun light (in units of W/m^2). Photosynthetically active radiation only includes light with wavelengths from 400 to 700 nm, roughly the same wavelengths visible to the human eye. Light within this part of the spectrum can be used by plants to drive photosynthesis and is measured in units of $\mu mol/m^2/s$. Thus, measuring shortwave radiation treats light as an electromagnetic wave and determines the energy in that radiation, while photosynthetically active radiation treats light as individual light particles (photons) and determines the number of photons in the incoming radiation.

Photosynthetically active radiation is normally measured using quantum sensors. Since these sensors measure the light that plants can use for photosynthesis, quantum sensors are often used when the collected data are needed for plant growth models. Such models can be coupled to water use models as well, in which case quantum sensors can be used for irrigation management. However, weather stations typically do not include quantum sensors. Photosynthetically active radiation data are used in both very simple (van Iersel et al, 2010) and complex water use models (Bauerle and Bowden, 2011)

Measuring shortwave radiation is critical in determining the energy balance of a leaf or crop. Energy balance calculations are used in the FAO Penman-Monteith model of ET and shortwave radiation measurements are thus critical for weather stations, if the weather data are to be used for ET modeling. Sensors that measure total solar radiation are referred to as pyranometers and normally part of weather stations, so these data are readily available.

Light intensities also are commonly measured with photometric sensors (although not as part of weather stations), in units of lux, lumens, or footcandles. Photometric sensors measure how well humans can detect the light. Since the sensitivity of the human eye is very different from the way plants perceive light, these measures should not be used for irrigation control purposes.

The calibration of light sensors drifts gradually over time, and often in an unpredictable way. To assure long term reliability, sensors need to be recalibrated ever 2-3 years (see manufacturers info for more details). Recalibration requires a standard light source and generally needs to be done by the manufacturer.

Temperature and relative humidity

Although very different, temperature and relative humidity are discussed together, because their effects on plant water are interdependent. Specifically, relative humidity itself does not have a direct impact on (evapo)transpiration. Instead evapotranspiration depends greatly on the vapor pressure deficit, which is a function of both temperature and relative humidity. To better understand this relationship, a clear understanding of some key terms is needed.

- Vapor pressure (e) is a measure of the actual amount of water vapor in the air. Vapor pressure is expressed in pressure units (kPa, mbar).
- Saturation vapor pressure (e_s) is a measure of the maximum amount of water vapor the air can hold. This is a function of temperature, with warmer air being able to hold more water. Saturation vapor pressure is expressed in pressure units (kPa, mbar).
- Vapor pressure deficit (VPD) is the difference between the maximum amount of water the air can hold and the actual amount of water vapor in the air ($e_s - e$).
- Relative humidity (RH) is the ratio between the actual amount of water vapor in the air and the maximum amount of water vapor the air can hold. It is most commonly expressed as a % ($e/e_s \times 100$).
- Dew point temperature is the temperature to which the air must be cooled to completely saturate the air with water vapor (*i.e.* reach 100% RH). When the dew point is reached, dew (condensation) will form if the temperature drops further.
- Dry bulb temperature is the actual temperature of the air
- Wet bulb temperature is the temperature of a thermometer covered with a wet wick and exposed to air flow. Evaporation of water from the wick will cool the thermometer, and the wet bulb temperature is thus always lower than the air temperature, but higher than the dew point(unless RH = 100% in which case wet bulb temperature, dry bulb temperature, and dew point are the same).

The driving force for evapotranspiration is VPD, but unfortunately, we cannot measure VPD directly. Weather stations normally determine VPD from the dry bulb temperature and relative humidity. For applications that require great accuracy, dry bulb and dew point can be measured and used to calculate VPD, but accurate dew point measurements are too expensive and technically challenging for use in irrigation management.

Typically, weather stations include a temperature sensor and relative humidity sensor. There are many different types of temperature sensors,, but weather stations most commonly use either resistance temperature detectors (RTD) or thermistors. Both sensor types are based on the same principle: the electrical resistance of the RTD element changes with temperature and the resistance of the element is measured. This measured resistance is then used to determine the temperature. Although temperature measurements seem simple, larger errors can occur if the sensor is not used properly. Most importantly, sensors should always be shaded and preferably aspirated.

Relative humidity is normally measured using capacitive sensors. These sensors contain a substrate between two electrodes and the amount of water the substrate absorbs depends on the relative humidity. The two electrodes are then used to measure the capacitance (for more details, see the section on capacitance soil moisture sensors) of the substrate and the resulting measurement is converted to a relative humidity value. The calibration of humidity sensors normally drifts gradually over time and these sensors should be recalibrated every 2-3 years to assure that the readings are accuracy.

Automated weather stations can then calculate the saturation vapor pressure, actual vapor pressure, and vapor pressure deficit from the temperature and humidity values.

Wind
Wind affects evapotranspiration, because air movement moves the humid air away from the canopy or soil and reduces the boundary layer resistance for water movement from the soil or crop to the air. Wind direction is generally less critical for irrigation management, but is measured by many common weather stations as well.

The most common method to measure wind speed is with cup anemometers. The wind causes the cups to rotate around a vertical shaft and the number of rotations within a particular time interval is measured to determine the wind speed. Thus type of anemometer is normally present on weather stations.

Another type of anemometer on weather stations is the windmill type, where a propeller is spun by the wind and the rotations of the propeller are measured. To assure that the propeller is perpendicular to the wind, a wind vane is normally used to align the instrument to the prevailing wind direction.
Hot wire anemometers are used more in research applications and consist of wire with an electrical current going through it. This current changes the temperature and thus the electrical resistance of the wire. Wind will cool the wire and the actual temperature and

resistance of the wire are thus dependent on the wind speed. The resistance of the wire can be measured using several different approaches, but the basic operating principle of all hot wire anemometers is the same.

Wind direction. Although generally not critical for irrigation applications, wind direction is normally measured by weather stations, using a vane. This vane can rotate and its angle depends on the prevailing wind direction. At very low wind speed, the wind may not have enough force to push the vane around, and wind direction measurements can become inaccurate.

Rain

Rainfall is obviously critical in irrigation applications and is generally measured using a tipping bucket rain gauge. Rainfall is collected into a funnel and the water is directed towards a spoon-like device. When enough water collects in this spoon, it will tip, causing an electrical signal to be sent (using a reed switch). Weather station rain gauges typically have a resolution of 0.2 mm or 0.01". Rainfall can also be measured using simple rain gauges, which vary greatly in their design. Simple rain gauges do not allow for automated data collection and are therefore not used as part of weather stations.

For irrigation purposes, it is not always necessary to know how much rain has fallen. Some irrigation systems simply have a rain sensor that can turn off irrigation when it is raining, without measuring how much rain is actually falling

Ideally rain gauges would not just determine the daily amount of rainfall, but also the intensity of the rainfall. Rainfall intensity in many situations will help determine how much water will infiltrate the soil and how much water is likely to be lost as surface runoff. Although most automated weather stations are capable of measuring this, they are often not configured to do so. This is an area where it would be easy to make progress towards making weather data more usable.

Soil vs. Plant Sensing

Irrigation decisions can be made by measuring the water status of the soil or crop and there is no agreement about which of these approaches is better. Proponents of measuring crop water status argue that the goal of irrigation is to assure adequate water availability to the crop and that crop water status is therefore the best indicator of whether irrigation is needed. However, crop water status is generally more difficult and expensive to measure than soil water content. In addition, crop water status is not only affected by the availability of water in the soil, but also by short term changes in weather (such as a clouds passing over) and by diseases and pests (particular those that affect the root system and thus the water uptake of the crop).

Soil water measurements have the advantage that they are relatively easy to make and automate. In addition, using soil water status to make irrigation decisions results in a simple feedback system: a low soil water content will trigger irrigation, which increases soil water content and indicates that irrigation is no longer needed.

Both crop and soil water status measurements need to take into account spatial variability. Soils are often not homogenous, resulting in spatial differences in soil water content. Whenever possible, such spatial variability should be quantified and the placement of sensors should take into account this spatial variability. In many cases this means that at least some sensors should be placed in the driest part of the field to assure that this part of the field receives adequate water.

Crops, likewise, are not homogenous. Spatial variability in the crop can result from natural variability among the plants, spatial variability of the soil, fertilizer placement, or environmental gradients within the field. In addition, there are distinct diurnal patterns in crop water status that make these data difficult to interpret. If individual plants are monitored to make irrigation decisions, larger plants may need to be monitored to assure that those plants receive adequate water. Remote sensing applications can alleviate issues related to spatial variability to some extent, either by measuring many plants and reporting an average or by mapping the spatial variability. For an excellent review on the implications of spatial and temporal variation on irrigation management, see the reviews by Jones (2004, 2007).

In many cases, the largest reason for spatial variability may actually be the design of the irrigation system itself: if the uniformity of the irrigation system is not good, spatial variability in soil water content and plant growth will be the inevitable result. Thus, any approach to precision irrigation needs to start with proper design, installation, and maintenance of the irrigation system. However, those topics go beyond the scope of this paper and are discussed in many other irrigation association papers.

Sensing Soil Water

Water content vs. matric potential
Two basic properties of soil (or in the case of greenhouse and nursery production, soilless substrates) can be measured, soil water potential and soil matric potential. There is no agreement which measure is better suited for irrigation management (see Jones, 2007).

Soil water content sensors, as the name implies, measure the amount of water in the soil, while matric potential sensors measure how easy it is for plants to extract water from the soil. Matric

potential and soil water content are related to each other, but this relationship is different for different soils and can be determined from soil moisture retention curves, which show the relationship between substrate water content and matric potential (Fig. 1).
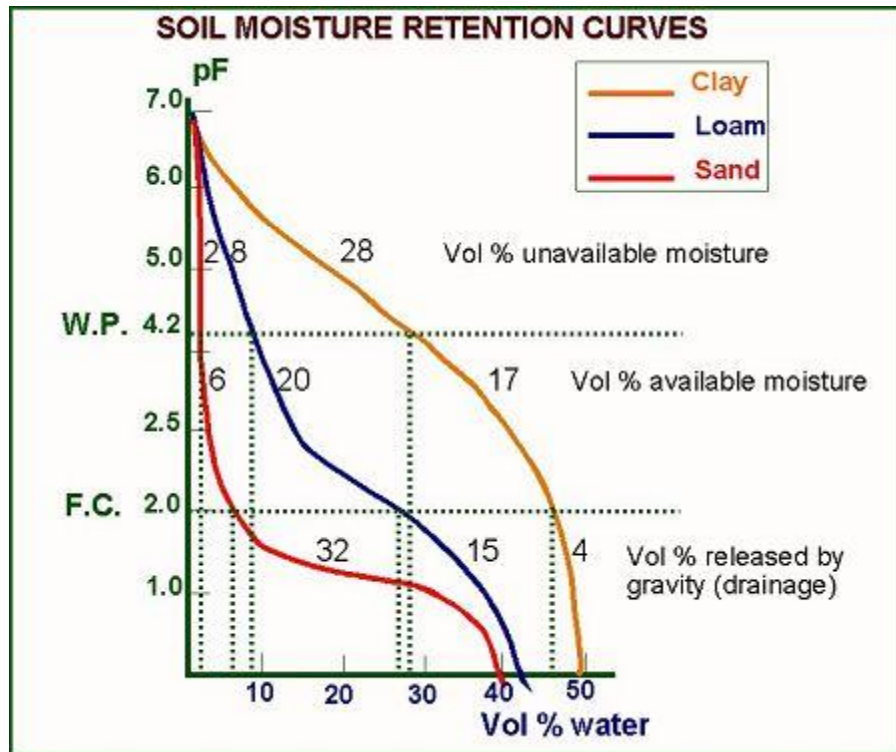

Figure 1. Typical soil moisture retention curves for thee different soil types. Soil matric potential is expressed on a logarithmic scale (y-axis, pF). W.P. is the permanent wilting point and F.C. is field capacity.

Thus, soil water content measurements indicate how much water is present, but not whether this water is actually available to the crop. This is critical in understanding the limitations of soil water content sensors: a soil water content of, for example, 20% provides absolutely no usable information about whether the water is plant available and whether or not irrigation is needed. In soils with a high clay content, a 20% water content likely means that there is little or no plant available water in the soil: the water is bound too tightly to the soil particles and plants cannot easily access that water. In that case irrigation is needed. In a sandy soil, on the other hand, 20% may be near field capacity and the soil water is readily available to the plants. Irrigation likely would simply result in draining of water below the root zone. To be able to interpret soil water content measurements, a basic understanding of soil properties is absolutely essential. When this information is available, soil water content measurements make it very easy to use those data for irrigation management, because it becomes very easy to calculate how much water needs to be applied when the irrigation is turned on. And if the flow rate of the irrigation system is known, it is simple to determine for how long to run the irrigation.

Soil matric potential has the advantage that it directly determines whether the soil water is available to the plants. Once an appropriate threshold for a particular plant/crop has been determined, this threshold can be used in different situations, regardless of soil type. However, matric potential data provide no information on how much water should be applied. To determine this, an understanding of the soil properties is required.

Water content sensing

The most accurate method to measure soil water content is with the use of a neutron probe. Neutron probes contain the radioactive element Beryllium. Beryllium emits 'fast' neutrons and when these neutrons collide with water molecules, they slow down and some of them will bounce back to a detector inside the probe. These slow neutrons are measured and used to determine the soil water content. Unfortunately, neutron probes are expensive and require special handling due to the emitted radiation. Use of neutron probes has thus been largely limited to research.

More common probes take advantage of the high dielectric of water. The dielectric refers to the interaction of water molecules and an electromagnetic wave or field that is applied to the soil. Most soil materials have a dielectric of about 4, air has a dielectric of 1, and water has a dielectric of about 80. Thus, changes in soil water content have a drastic effect on the total dielectric of the moist soil. Different sensors detect these changes in the dielectric of the soil and the dielectric values then are converted to soil water content. Among sensor types that use the dielectric properties of soils are time-domain reflectivity (TDR) sensors, time domain transmisometry (TDT), and capacitance sensors. TDR has long been the standard method of measuring the dielectric properties of soil; the sensors themselves are cheap, but an expensive meter is needed to measure the sensors. In the last decade, other approaches have been developed to use the dielectric properties of soils (TDT, capacitance). These newer sensors do not require an expensive meter and have facilitated the incorporation of soil moisture sensors into irrigation control systems.

Despite the claims from some manufacturers, all sensors that rely on the dielectric properties of soils benefit from a soil specific calibration. There are large enough differences in the dielectric properties of different types of soils to affect the measured dielectric of the soil. This becomes especially critical if such sensors are used in soils with high organic matter content, high salinity, or in soilless, highly porous substrates used in horticulture (*e.g.* Crespo and van Iersel, 2011).

Matric potential sensing

Matric potential of the soil is most commonly measured using tensiometers. Tensiometers measure soil matric potential (suction) directly, and the data do not depend on soil type or texture. No soil specific calibration is needed. Tensiometers do require routine maintenance, because they contain water which needs to be replenished on a regular basis. Tensiometers only measure matric potential within a fairly limited (wet) range, but this is generally adequate for irrigation in horticultural or agronomic applications.

A different approach to sensing matric potential is the use of gypsum blocks or Watermark sensors. These sensors have a matrix that can absorb and desorb water in response to changes in soil matric potential. The electric resistance of this matrix changes as the amount of water in the matrix changes, and the electrical resistance is measured and then converted to a soil matric potential. Gypsum blocks have the disadvantage that they gradually dissolve over time, which led to the development of the Watermark sensor, which does not have this problem. Because the electrical resistance of the matrix does not only depend on water content but also on dissolved ions, these sensors tend to be sensitive to changes in soil electrical conductivity, and thus fertility and salinity.

More recently, hybrid sensors have been developed that apply the principle of dielectric sensors to determine matric potential. A dielectric sensor is embedded with a ceramic material (matrix) and the matric potential of this ceramic material equilibrates with the matric potential of the surrounding soil. The dielectric sensor is then used to measure the dielectric of the ceramic material and this value is then converted to a soil matric potential.

Soil Salinity

Salinity measurements are important in irrigation methods, because irrigation not only serves to apply water to a crop, but also plays a critical role in the prevention of salt build up in the soil. Salinity levels in soils are generally determined from the ability of a soil to conduct electricity (electrical conductivity or EC), which can be expressed in dS/m or mS/cm (those units are equivalent).

The most accurate methods of determining soil salinity are lab-based tests, where soil samples are collected and sent off to an analytical lab for analysis. It is important to note that different labs may use different methods to measure salt concentrations in the soil, and that results from different labs may thus not be comparable. The most common methods are the saturated soil extracted and 1:2 and 1:5 dilution technique. Dilution techniques results in lower values than the SSE method when equal amounts of soils are present.

Soil EC can also be determined from the dielectric properties of soils, which makes it possible for techniques like TDR to measure both soil water content and EC simultaneously (Dalton and van Genuchten, 1986). Likewise, the EC of soils can be measured using electrodes inserted in the soil and measuring the conductance (the inverse of resistance) of the soil. One drawback to both of these methods is that they measure a property referred to as the bulk soil EC, or the ability of the combination of soil particles, air spaces, and the soil solution to conduct electricity. This property has little practical value, since it is difficult to convert that value to either the total amount of salts present in the soil (which is critical for salinity management) or the EC of the soil solution (which determines the physiological responses of plants to salinity. Although models have been proposed for converting bulk soil EC to solution EC (e.g. Hilhorst, 2000), there are questions about the accuracy of the various methods. Advances in our ability to measure soil EC could have great benefits for our ability to manage both salinity and fertilizer applications.

Sensing Plants

Many different approaches to sensing plant water status have been used, and this is just a selection of the many methods available. The goal of sensing plant water status is to determine whether the plant is under stress and thus needs water. This also goes to one fundamental weakness of any plant-based sensing method: by the time a stress can be detected, productivity likely has been lost already. That may not matter in most landscape situations, but in horticultural and agronomic applications, where maximizing yield is an important goal, plant-based methods may result in yield losses.

Sap flow

Different methods for measuring the flow of xylem sap through plants have been used and tried for irrigation control. The most common methods are the heat balance method (where a small part of stem is heated and the heat balance of the stem is calculated) and the heat pulse method (where needles inserted in the stem are heated and the heat dissipation is measured). These methods can give accurate information about sap flow through the plants, but the data can be difficult to use for automated irrigation management. Sap flow not only depends on the availability of water in the soil, but also on the weather conditions, and health of the plants. Thus, a decrease in sap flow may not indicate the need for irrigation, but could simple be due to clouds passing over. This makes automation based on these data difficult, but the results still provide valuable insights into the water dynamics of the crop.

Leaf temperature

A simple method to get an indication of the level of drought stress a crop is exposed to is to use of leaf or canopy temperature data and to determine how this differs from air temperature.

Measuring leaf (or canopy) and air temperature can be used to calculate a crop water stress index (CWSI). Irrigation decisions are based on canopy foliage and air temperature under given meteorological conditions in comparison with canopy foliage temperature of a well-watered crop. This approach requires an infrared thermometer - a hand-held or remotely mounted device that can measure canopy temperature. This approach is based on the principle that transpiration cools the canopy and a well-watered canopy, therefore typically has a temperature lower than the air temperature, while a drought stressed canopy typically will have a higher temperature than the air.

The CWSI is calculated as:

$$CWSI = \frac{(T_f - T_a) - (T_f^* - T_a)}{(T_f - T_a)_{max} - (T_f^* - T_a)} , \text{ where}$$

> $T_f - T_a$ = Foliage-air temperature difference of crop in question
> $T_f^* - T_a$ = Foliage-air temperature difference of well-watered crop under same environmental conditions.
> $(T_f - T_a)_{max}$ = Foliage-air temperature difference when crop is maximally stressed (transpiration = 0) under same environmental conditions.

The CWSI is therefore a unitless number between 0 and 1, giving a "relative" indication of stress level. A value of 0 indicates that the crop is not water stressed at all, while a value of 1 indicates the maximum stress level.

Leaf wetness

Leaf wetness sensors determine are designed to mimic leaves and measure when and for how long the leaves are wet. This is particularly important for the prevention of a variety of foliar diseases, since certain pathogens require liquid water on the leaf surfaces to complete their life cycle. Leaf wetness can thus be used to help determine how different irrigation schedules may impact disease development. Two types of leaf wetness sensors are commonly used: a) sensors that measure the electrical resistance along the outer surface of the sensor. These sensors normally have two electrodes that form a grid throughout the sensor and the resistance between those two sensors is measured. When the sensor is wet, the water will conduct electricity and the resistance drops. The other type of leaf wetness sensor takes advantage of the dielectric properties of water and is essentially a modified soil moisture sensor. Rather than measuring soil water, these sensors simply measure the presence of water on the surface of the sensor. Both types of leaf wetness sensor are sensitive to dirt accumulation and should be kept clean.

Remote sensing

The crop water status can be determined using spectral reflectance measurements. When light hits a leaf, there are three possible fates for any particular photon (light particle): it can be absorbed by the leaf (pigments), reflected, or transmitted. Light reflectance can change dramatically when plants are exposed to drought stress, especially in the near infra-red part of the spectrum (just above 700 nm and not visible to the human eye). By measuring the reflectance of light of different wavelengths [normally red (R) and near infra-red (NIR)], a ratio can be calculated that indicates the stress level of the plant or crop. Among the ratios being used are:

- The normalized difference vegetation index or NDVI = (NIR-R)/(NIR +R)
- The ratio vegetation index or RVI = NIR/R

Neither index is a direct indicator of drought stress; other factors, and especially how much of the plant canopy covers the soil, affect these indexes as well. Thus, these indexes do not have some magical threshold below which the crop needs water; instead it is important to look at changes in the values of these indexes over time.

Many other methods of remote sensing have been used for irrigation control. For a more comprehensive overview of remote sensing techniques, see Bastiaanssen (1998).

Sensing the Irrigation System

Sensors are not only useful to determine when and how much to irrigate, but also play an important role in checking the performance of the irrigation system and can be used to detect maintenance problems. The two most useful things to measure are flow rate and water pressure.

Flow meters

Flow meters should be part of any commercial irrigation systems. Not only do they provide a record of water use, they also can be used for trouble shooting purposes, such as leak detection. There are many flow meters available that can easily be incorporated into larger sensor networks. The most common flow meters have a paddle wheel that rotates faster as the flow rate increases, but many other technologies are available as well.

Water pressure

Measuring the water pressure in the irrigation system is valuable for leak detection (since leaks can reduce water pressure), but also to assure that there is adequate pressure for proper operation of the irrigation system. A lack of pressure is especially common in large irrigation systems that use multiple valves. If too many irrigation valves open at once, water pressure may be too low for the irrigation system to irrigate properly.

Conclusions

Sensing environmental and other conditions can provide information that can be used to greatly increase the efficiency of irrigation systems. It is important to realize that sensors can be used to collect large amounts of data, but these data have little value with efficient ways to collect, store and process them. First of all, for large scale sensing, appropriate hardware is needed. An example of the development of the hardware needed for wireless sensor networks is described by Kantor et al (2012). Along with this hardware a software interface (or graphical user interface is needed to present the data has in such a way that it is converted into usable, actionable information (see Kohanbash and Kantor, 2012). Our group has successfully used newly developed hardware and software for on-farm irrigation scheduling (Chappell and van Iersel, 2012, Lea-Cox and Belyaneh, 2012). Irrigation can be based on soil/substrate water content measurement or on models that predict crop water use (e.g., Kim, 2012). A survey of the greenhouse and nursery industry has shown that there is widespread interest in the use of sensor networks for irrigation monitoring and control (Majsztrik et al, 2012) and this may help move the industry from irrigation practices that rely heavily on qualitative indicators of crop water needs to more quantitative methods. We have already seen that such a switch to more quantitative irrigation methods can help save large amounts of water (van Iersel, et al, 2009) and increase growers profits (Chappell et al, 2012).

Acknowledgements

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