All About Sensors

Sensors are a critical part of the wireless sensor networks developed as part of this project. The goals of this learning module are to:

- Give you a better understanding of what a sensor is
- Learn some basic concepts about sensor accuracy and data collection options
- Discuss how various sensors can be used to help you irrigate more efficiently

This introductory learning module is designed to present some basic concepts. Where appropriate, we have included links to other learning modules that provide more in-depth information on various topics.

1. What is a sensor?

A sensor can be defined as any instrument that measures some type of physical or chemical characteristic and converts that measurement into a signal that can be read by an observer or automated data collection system. We are all familiar with sensors and use them on a daily basis: among the simplest of sensors are thermometers to measure temperature and measuring tapes to measure distance.

Getting readings from a sensor can be as simple as using a visual reference scale built into the sensor (such as basic thermometer or measuring tape), or it may involve reading a digital/analog signal produced by a sensor. In the latter case, the sensor is combined with a meter. The terms sensors and meters are often used interchangeably, but they actually refer to different things: sensors respond to a physical or chemical condition and produce a signal; meters can be used to measure and display that signal in an understandable format. In many cases, sensors and meters are used together and they may be combined into a single instrument.

Figure 1. Decagon's VP3 sensor is a digital sensor. The sensor measures temperature and relative humidity and then calculates vapor pressure deficit (Photo courtesy of Decagon Devices).

1.1 Digital vs analog sensors

Older, analog sensors typically produce a voltage or current output in response to the characteristic (light, temperature, etc.) that they measure. Meters are then used to measure the resulting voltage or current. That voltage or current signal can then be converted into a meaningful number by applying a calibration to the measured signal. Accurate calibrations are critical for converting a sensor signal into a usable measurement.

Many newer sensors provide a digital output. Such sensors contain a micro-processor that takes the signal from the sensor(s) and subsequently uses that signal to do all kinds of calculations. You can think of digital sensors as smart sensors: they not only can measure things, they can also process the collected data. A fairly simply example of a digital sensor is Decagon's VP3 sensor. This sensor measures temperature and relative humidity and then uses those measurements to calculate vapor pressure deficit.

With the ever decreasing cost and increasing capabilities of micro-processors, digital sensors are becoming increasingly popular and powerful.

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2. Data collection

When you use sensors to make measurements, having a record of the data is often useful. Although it is possible to simply write down all the data, that is time consuming, potentially error-prone, and those hand-written data may be difficult to use later. If the data taken by a sensor are important, it is useful to have a device that can store the data and easily export them into a spreadsheet or a database program.

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3. Handheld meters

For many sensors, handheld meters are available that can be used to both measure sensors and store data. Such meters can typically be connected to a computer using a USB cable, and data can be transferred to the computer and imported into a spreadsheet. Spreadsheets typically provide a convenient format for storing and further manipulating the data.

Handheld meters are probably most useful when a small number of sensors are used for taking spot measurements. They become too labor intensive when many sensors need to be measured.

Figure 2. Decagon's ProCheck handheld meter can be used with a wide variety of Decagon sensors. Data are stored in the ProCheck and can be transferred to a computer (Photo courtesy of Decagon Devices).

4. Datalogging systems

When a large number of sensors are used, a datalogger is the most convenient method to collect the data. A datalogger is an instrument that can automatically measure sensors and store the data, typically at user-specified intervals. The EM50 datalogger (Decagon) is an example of such a logger, and it can be used with many different sensors sold by Decagon. To transfer the data to a computer, the datalogger is connected to a computer using a USB cable. The data can then be viewed using Decagon software, and imported into a spreadsheet for further analysis.

Figure 3. An EM50 datalogger from Decagon can measure and store data from up to five sensors (Photo courtesy of Decagon Devices).

A more advanced option is a datalogger with a radio or cell modem built in. Such data loggers can transfer data either by radio or cell phone network to a receiver or basestation that is connected to a computer. Specialized software (i.e., DataTrac) is then used to display and export data in a format compatible with spreadsheets. Such systems are often referred to as wireless sensor networks, even though the sensors may still be connected by a wire to the datalogger. Completely wireless systems are also available. In such a system, the sensor has a radio that transmits the data to a nearby datalogger, which can then send the data to a computer.

Not surprisingly, the more capabilities a system has, the more expensive it tends to be. There is no single best solution for all circumstances; this will largely depend on how the data are used. If the data are used to create a permanent record of the conditions during a particular cropping cycle, having instant and easy access to the data may not be critical. However, if the data are used to make important decisions regarding production practices, such as irrigation or fertilization, a more advanced system will likely be needed.
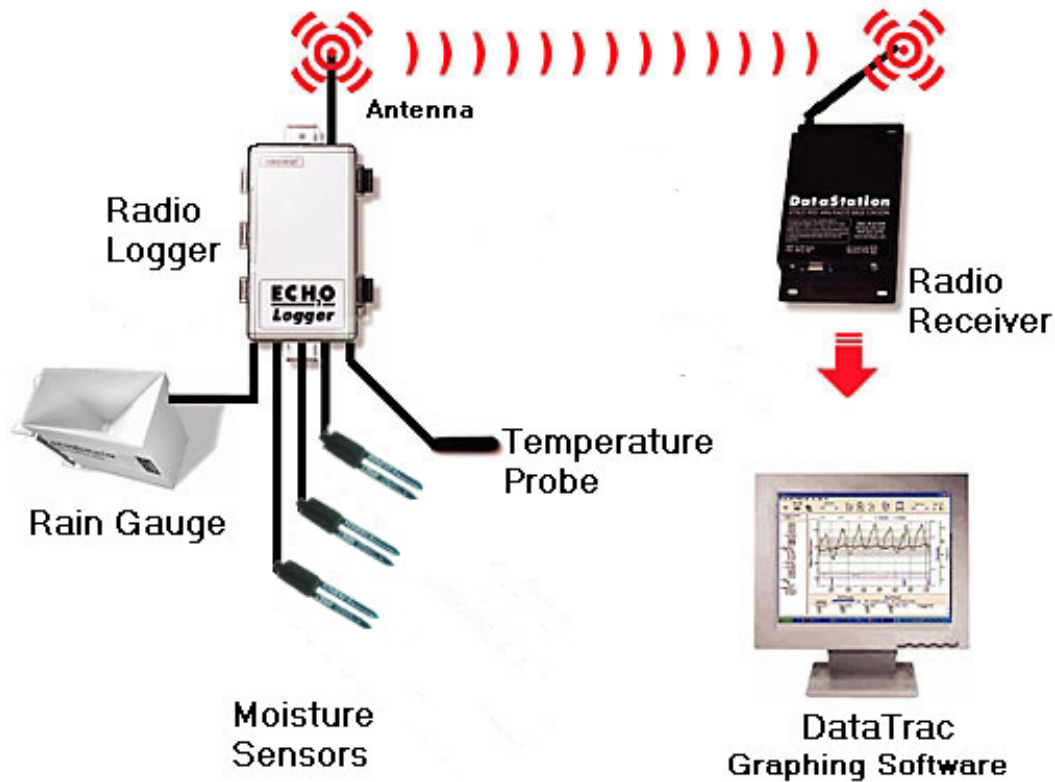

Figure 4. Some data collection systems can send the collected data to a computer by radio. Decagon's EM50R is an example. A dedicated receiver is needed to communicate with the logger (Diagram courtesy of Decagon Devices).

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5.1 Calibration

Sensors typically come with a calibration that converts the signal produced by the sensor into a usable value. For example, a light (quantum) sensor may produce a 1 mV output for every 5 µmol/m^2/s of light it receives. That light sensor would have a calibration constant of 5 µmol/m^2/s per mV and a meter or microprocessor would multiply the measured voltage by 5 to give you the light level in units of µmol/m^2/s.

Sensors normally come with factory calibrations that are usually specified in the manual or on a calibration certificate. Manufacturers generally also indicate how long that calibration is valid. The calibration of many sensors changes over time and sensors need to be recalibrated at regular intervals to assure that they remain accurate. How often sensors should be recalibrated will depend on the sensor. Users should follow the guidelines from the manufacturer. Sensors that have not been recalibrated for extended periods are likely to give inaccurate results.

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5. Sensor accuracy

Collecting data of any kind is not useful if you do not know how accurate the data are. In many cases, it may be better to have no data than to have bad or inaccurate data, since bad data will mislead you and may cause you to make wrong decisions. So, understanding the accuracy of your sensors is important, but, unfortunately, it is not always easy. There are several basic concepts that users need to be aware of to be able to determine the accuracy of a sensor. Reputable manufacturers will normally include this information in their sensors' specifications.

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5.2. Precision

The precision of a measurement is the degree to which repeated measurements under unchanged conditions show the same results, In other words, if you measure the same thing 10 times, how similar are your 10 results? Most likely, not all 10 measurements will give the exact same results, but how different are they? Note that precision is very different from accuracy: you may get 10 very similar results, but they could all be wrong. In that case the measurements are precise, but not accurate.

Precision can be separated into two components:

Repeatability — the variation in measurements found when keeping the instrument, user, and conditions constant while the measurements are repeated during a short time period.

Reproducibility — the variation in measurements while using the same measurement process among different sensors/meters and operators, and over longer time periods.

Figure 5. An example of high precision, but low accuracy, with the dots representing measurements and the bull's eye representing the true value. All measurements are very similar, but not close to the true value.

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5.3 Accuracy

The accuracy of a measurement is the degree of closeness of the measurement to the actual (true) value. Accuracy is also referred to as the measurement error. Although this may seem like a simple concept, the accuracy of sensors can be very hard to determine. This typically requires a 'standard', in the case of a scale, that would be an item of a known weight. For many other sensors, it is difficult for users to get a reliable standard to determine accuracy. Manufacturers typically have calibration procedures, using standards that are traceable to the National Institute of Standards and Technology (NIST). That allows the manufacturers to determine accuracy information in their specifications.

The ideal sensor would have good accuracy and good precision. Note that accuracy can be improved through proper calibration, while precision normally cannot. In some cases, sensors with good precision, but not good accuracy, may still be able to fulfill their intended purpose. For example, for irrigation control based on soil moisture sensors, it may be good enough to be able to precisely measure changes in soil water content (which a sensor with good precision can do), even if the accuracy is not good (all measured soil water contents would be higher or lower than the true water content).
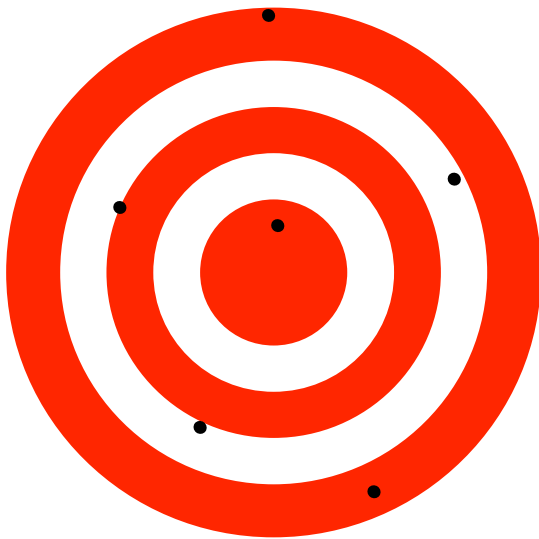

Figure 6. An example of good accuracy, but poor precision. On <u>average,</u> the data are close to the bull's eye, but there individaul measurements vary widely.

Figure 7. An example of both accuracy and precision: all measurement data are close to the bull's eye.

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5.4 Resolution

The resolution of a sensor is the smallest change it can detect in the quantity that it is measuring. For example, many inexpensive kitchen scales have high resolution, meaning that they can display small changes in weight. If the smallest change in weight they can display is 0.01 gram, then that is the resolution of that scale.

Most newer sensors have much better resolution than either precision or accuracy. A kitchen scale may display weights with a resolution of 0.01 g, while the precision and accuracy likely are at best 1 gram. So the ability of the scale to display weights with very high resolution does not necessarily provide any usable information.

When looking at specifications for sensors, do not let high resolution fool you: it means nothing if the high resolution is not matched by both high precision and high accuracy.

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5.5 Improving accuracy

Good data are needed for good decision-making. And because no sensor is perfect, it is worthwhile to consider different ways in which accuracy can be improved. Calibration was discussed above. Another topic to consider is how much spatial variability there is in the parameter you're trying to measure. For example, greenhouses often have temperature gradients, especially when pad and fan cooling systems are used. If accurate temperature data are needed in such a greenhouse, it may be necessary to place thermometers in several different locations. That would allow users to quantify the temperature gradient that is present in the greenhouse. If users only want to know the average temperature, the temperature readings from multiple thermometers can be averaged.
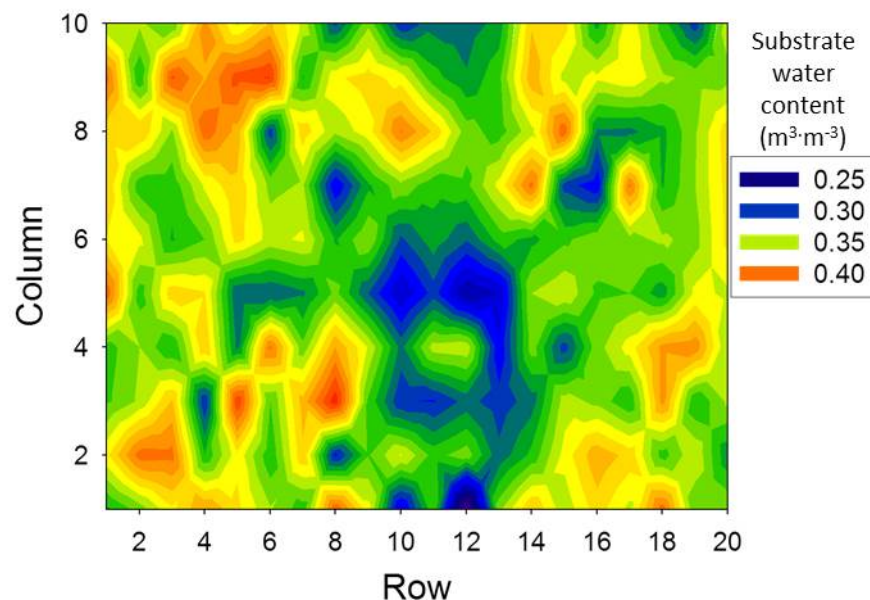

Figure 8. Spatial variability in substrate water content in a group of 200 plants (arranged in 20 rows of 10 plants each. Adapted from: van Iersel, Dove, and Burnett, 2011, *Acta Horticulturae* 893:1049-1056.

Alternatively, a single thermometer could be placed in a location that is representative for the entire greenhouse. In many cases, a central location is chosen. But keep in mind that this is not always representative. To truly find a representative location, it is necessary to first quantify the spatial variability. Spatial variability is also important when using soil moisture sensors. Soil/substrate moisture content is rarely, if ever, uniform throughout and within a single container, let alone an entire crop or a whole greenhouse or nursery. Spatial variability in soil or substrate moisture content can be the result of non-uniform irrigation (see learning module x.x), differences in plant size, or different micro-environments within a growing area (for

example, plants on the edge of a production block or bench typically dry out faster than those in the middle).

The greater the spatial variability, the more sensors are needed to get truly representative measurements. That said, we have had good success irrigating thousands of plants based on soil moisture sensor readings using only five soil moisture sensors. And at times, we have irrigated up to 2,000 plants using a single soil moisture sensor. With that single sensor, users cannot determine how much variability there is, but a single sensor can be indicative of changes in soil/substrate moisture over time. Note that the example here refers to differences in temperature or soil moisture content at different locations within a production area. But typically there are also spatial gradients within a container: the top part of the substrate normally is drier than the bottom part. To minimize variability, placing all sensors at the same depth is important.
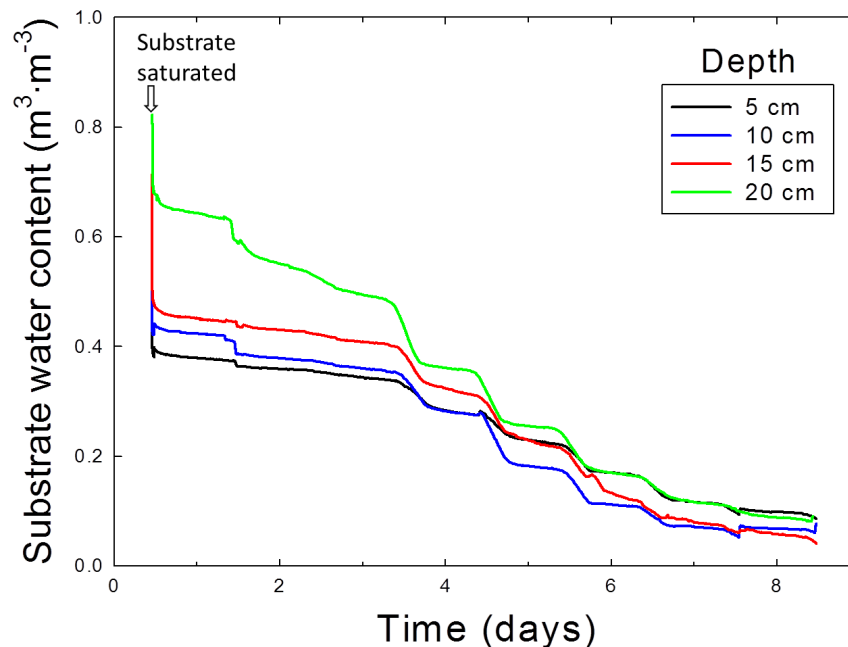

Figure 9. Temporal and spatial variability within a #2 container with a coleus plant. The container was watered thoroughly on day 0 and allowed to dry out after that. Initially, there is a largely spatial gradient within the container, with more water in the bottom. As the substrate dries out, the spatial gradient decreases and water content at all four depths becomes more similar. There also is temporal variability: the substrate water content at all depths decreases in a stepwise manner, because the plant uses more water during the day than at night.
Adapted from: van Iersel, Dove, and Burnett, 2011, *Acta Horticulturae* 893:1049-1056.

We do not have specific guidelines for how many sensors are needed in a specific situation; it depends on spatial variability and the level of accuracy that is required. In principle, more sensors are likely to provide better data, but this comes at a higher cost and the need for more maintenance.

In addition to spatial variability, there can also be temporal variability because the things we measure change over time. In the case of substrate water content, we typically see it decrease more rapidly during the day than at night and more rapidly on sunny, dry days than on overcast, humid days. Changes in substrate water content immediately after irrigation can be used to detect leaching: a very rapid decrease in substrate water content generally means that water is running out of the bottom of the container (or at least below the location of the sensor). If such information is important, data should be collected at short time intervals.

Using multiple sensors can often improve accuracy if the sensors are noisy (i.e., have poor precision). In such cases, multiple measurements can be averaged, reducing the noise and increasing the accuracy. One example is the measurement of light level in a greenhouse. There are many structures in a greenhouse that can shade a light sensor or may reflect light onto the light sensor. That can make light data quite noisy. Averaging multiple measurements can reduce the noise in the data and provide more representative data.

6. Sensors and irrigation systems

There are many sensors that can be used to assist in irrigation management. A very brief overview of such sensors is given here and many of these sensors are discussed in more detail elsewhere.

Weather data are important, because crop water use depends greatly on the weather. Details on weather stations and the sensors that can be included are discussed in a separate learning module.

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6.1 Soil moisture and EC sensors

Measuring soil moisture and electrical conductivity (EC) has obvious uses in irrigation and fertilization management. Using soil moisture sensors to control irrigation has been an important focus of the MINDS project. Likewise, EC measurements can be used to help make fertilization decisions. But keep in mind that it is still very difficult to get meaningful EC data with sensors that are currently available. Better sensors are needed before they can be used to make reliable fertilization decisions.

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6.2 Pressure sensors

In-line pressure sensors can be used to monitor water pressure and to assure that water pressure is optimal for your irrigation system. Pressure sensors can also be used to monitor whether valves are functioning, since the water pressure in irrigation laterals should decrease when the valve is opened. Leak detection is another potential application of pressure sensors. Water pressure should be similar throughout the main lines of an irrigation system (assuming there are no open valves).

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6.3 Flow meters

Every irrigation system should have at least one flow meter (near the water source) to monitor water usage. Flow meters can also be good tools to detect leaks: if the flow meter indicates that there is flow but all valves are closed, there must be a leak somewhere in the system. Having flow meters as part of your irrigation system not only helps you monitor how much water you use, it also provides a record of your practices and helps you to quantify changes in water when you change your irrigation practices.

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6.4 pH

pH sensors can easily be installed in-line and are especially useful if you have alkaline water and are injecting acid to bring the pH within an acceptable range. In-line pH sensors can help you keep track of whether the injection system is working properly.

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6.5 Remote sensing

Remote sensing refers to sensors that can measure crop parameters remotely by using sensors mounted above the crop, on drones or airplanes, or even satellites. These are not commonly used yet, but there are sensors that can measure canopy temperature (using infra-red thermometers), canopy size (NDVI or normalized difference vegetation index), or overall crop stress (photochemical reflection index, which unfortunately is not very sensitive to drought stress). In the future, additional remote sensors that can measure plant water and nutrient status may be developed. Time will tell how common these sensors will become in production horticulture.

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