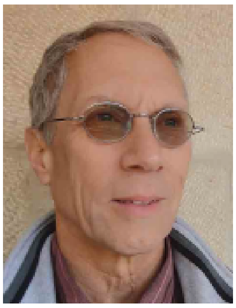
Ground-based plant and climate monitoring of crops for tracking water use and water status

By Dr. Shabtai Cohen



OVERVIEW

Ground-based plant and climate monitoring today includes a range of techniques and associated instrumentation used to monitor plants in the field with sensors mounted on or inside the plant, as well as nearby. These methods today can compete with or supplement remote sensing, which is typically done from airborne or satellite platforms. As the range of electronic technologies advances, the options and technological solutions for monitoring plants improve and decrease in price. We have developed and adapted a group of sensors to monitor water use and water status of crops, as well as climactic parameters, and developed methods to compute atmospheric "dryness" for setting amounts of irrigation over the range of conditions in Israel. In many cases, the use of these technologies has led to large reductions in the amount of water used for irrigation, resulting in a significant savings of capital for farmers and water for the Israeli economy. Herewith are reviewed some of the technologies and sensors that are being developed and used for sensing plant water status and water use, and climate demand for water, at the Volcani Center. Experiments using sensors for irrigation research in deciduous orchards and screen-covered banana plantings are described.

INTRODUCTION

A number of years ago I had the unfortunate opportunity to visit a relative who was in the hospital and unconscious after an accident. As a layman, it was not clear to me what his condition was but the displays from the sensing technologies being used to monitor what was going on in his body looked good and were helping the doctors get important information needed for treatment. These sensing systems, which included pulse, blood pressure, blood oxygen and a range of other parameters that many of us are somewhat familiar with, told a story about how well his body was functioning. The sensors were all sending information to one computer that was logging and analyzing the data. Today we expect to have these systems in our hospitals and they are allowing doctors to have unprecedented amounts of highly detailed information for basing their decisions. Actually, in some cases, 'decision support systems' have been developed based on our understanding of bodily functions, which automatically recommend a medical course of action or make decisions automatically. Similarly, agricultural scientists have developed a range of sensors and monitoring techniques to sense climate around the crop and plant processes, analyze the data to give useful information to researchers and farmers, and in some cases recommend or control farm decisions. We can say that these technologies are helping the plant communicate with us.

At the Volcani Center, Dr. Josef Tanny and I, along with colleagues, students and engineers, have developed, adapted and implemented a number of sensor systems to monitor climate, atmosphere and plant water use and morphology. We have used these technologies in a wide range of projects, which, besides agricultural water use, include human thermal comfort in urban settings, plant-disease epidemics, and managing reservoirs and forests. However, most of our work focuses on how plants feel, how much water they use and need, and how much to irrigate. This information is vital for fine tuning irrigation and improving agricultural water use efficiency, a major objective of agricultural research in Israel. These technologies include the ability to:

1. Measure sap flow in plants. Sap is the water that moves up through the stem and evaporates into the atmosphere. Knowing how much sap is lost is a key factor in deciding how much to irrigate.

2. Monitor the vertical flux of water vapor above crops and forests to know how much water the whole agricultural system or ecosystem is using and is returning to the atmosphere above. Knowing how large systems interact with the atmosphere is important for management and for improving our ability to predict weather as well as climate change.

3. Measure atmospheric dryness from climate sensors at special weather stations, many of which have been integrated into the Israeli agro-meteorological grid. Water coming through the plant evaporates into the atmosphere due to this atmospheric dryness, and we irrigate accordingly.

4. Stems of healthy plants grow during at least part of the year, and they also contract and expand slightly during the course of a day as the plant sucks water from the soil or relaxes at night. The magnitude of the minute contractions and expansions as well as the growth rate can indicate whether the plant has enough water or is suffering from drought. Fruits and leaves grow during the season and their daily growth rate can also be indicative of plant health.

The past 10 years have seen an explosion in the development and use of miniature advanced micro-processors and micro-controllers. These are small electronic boards that require very little electricity to operate, but are essentially computers designed to monitor and store information from a range of sensors as well as communicate with the outside world by transmitting the data to storage devices, cellphones and the internet. The price of these electronic boards has plummeted as they have gone into mass production, making advanced sensor platforms economical for use in the field, orchard or managed forest.
Electrical storage (in batteries) and increasing efficiency of solar charging systems to keep our systems operating continuously under field conditions are enabling us to deploy more of our sensor systems over longer periods of time (months and years).

Together the sensors, micro-processor/controllers and electrical support systems have led to an unprecedented ability to monitor plants in field situations. A few of the technologies and test cases are:

<u>Sap flow sensors</u>

Plants take up carbon dioxide from the atmosphere during photosynthesis to produce food for all life on our planet. But when they do that water is lost to the atmosphere as evaporation. Sap is the water that flows from the soil through the plant and into the leaves to provide the water needed during photosynthesis. Sap used by the plants must be resupplied to the soil as irrigation. Two types of sap flow sensors were developed at the Volcani Center in the 1980s and 1990s by a group of researchers led by Dr. Yehezkel Cohen. Both types of sensors are implementations of heat pulse technology. This technology uses a tiny heater that is placed in a medium where fluid is flowing. A pulse of electricity, usually for less than one second, is given to the heater, which can increase in temperature to 80 degrees centigrade. Although the heater cools quickly, the heat moves along with the liquid and is tracked by tiny thermometers. Analysis of the temperature signals gives the flow rate. One of the Volcani-developed systems is designed for trees and the second for herbaceous species including corn, cotton and pepper plants. A third technique, developed by a French scientist, which uses a continuously heated heater, called the "thermal dissipation" technique, is much cheaper to build and has been adapted in the past decade by our group for use on various tree species including citrus, deciduous orchards, banana plants and date palms. Adaptation of the sensor systems involved development of appropriate packaging for long-term survival in the field, the electronic backbone needed to operate the probes, connect them to micro-processors, and provide online communication from the field installations to a laboratory computer via cellphones or the internet. Some of the communication is already wireless and in the future it will all be wireless. We have also found that sap flow is variable inside the plants and between plants, so we have to monitor a number of plants to get accurate results. The need for many sensors in an experiment has led us to adapt technologies that we can build ourselves in the lab for very little money using relatively cheap, readily available parts.

<u>Eddy covariance, Surface Renewal, Flux Variance</u>

Water that evaporates from the leaves moves into the atmosphere around the plant and from there into the atmosphere above. Flow in the atmosphere is not smooth, but rather turbulent, as can be seen is a smoke trail that winds around instead of going straight. Air moves as parcels, which we can think of as gusts of wind. Sometimes parcels move upward and sometimes downward but, overall, evaporated water vapor from the plant moves upward. Measuring this movement involves tracking the upward and downward moving air parcels. A straightforward method for doing this, called the eddy covariance method, measures vertical wind speed and air humidity with very fast sensors, typically 10 times per second, and basic analysis of the data, which can be quite complex, is done automatically. Dr. Josef Tanny has been a pioneer in application of this method in Israeli agriculture, including use of the technique in crops grown under screens such as peppers and bananas. As with the sap flow measurements, knowledge of water evaporation from an agricultural field is vital for irrigation scheduling, but the eddy covariance equipment is too expensive for farmers. Other less demanding methods are being developed that take advantage of our understanding of water vapor movement in the lower atmosphere but require less expensive equipment, like minute electronic thermometers and radiation sensors.

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→ Atmospheric dryness or "Reference crop evapotranspiration"

Almost all Israeli farmers use electronic irrigation controllers and they adjust their irrigation according to atmospheric dryness, which is translated to irrigation amounts and computed from climate data that includes temperature, humidity, wind speed and solar radiation. The Israel Meteorological Service and the Ministry of Agriculture's Soil Conservation Department have set up a network of stations that monitor climate, compute atmospheric dryness and make that data available to everyone through their website (www.agrometeo.co.il) run by Marc Perel. A joint committee of the Ministry of Agriculture's extension service (Shaham), a Volcani representative, and the Israel Meteorological Service established standards for the calculation of atmospheric dryness in Israel, in accordance with international standards. The calculation is based on a basic understanding of water use of a well irrigated, cut grass field, which is significantly different from that of crops and forests in Israel. Ongoing research is focusing on improvements of the calculations for various situations, and adjusting the atmospheric dryness to get a reasonable number to put in our irrigation controllers. In the future, irrigation controllers with internet access will automatically adjust irrigation amounts daily according to the appropriate formula calculations that we are developing.

Stem growth and stem contractions:

Dendrometers – sensing stem contractions

As the soil around a plant's roots dries, the plant also dries slightly, which causes the plant to apply more suction at the roots and further dry out the soil. The suction, which is a result of the reduction in plant hydration, can be measured as plant water potential, a physical term. Plant water potential is currently considered the best indicator of how dry the plant "feels", but it is difficult to measure. Most of the changes in water potential in the stem cause shrinking (or expansion if water potential increases) of the soft tissues below the bark. The stem contractions are easily measured with a number of electronic transducers which translate the movement of the sensor into an electronic signal. Contractions of 10 microns (a hundredth of a mm) are relatively easy and cheap to measure, making the use of dendrometers (stem diameter sensors) popular, and some commercial companies are using them for informing irrigation scheduling. However, there are other things that influence the diameter of the stem and therefore the measurements can be ambiguous. Two of these are the stem growth and the movement of sugars in the stem during the day. Stem growth does not occur always, and can be seasonal. Sugar movement is also problematic. A current Ph.D. student, Ori Achiman, is developing a mathematical description of these relationships that should improve our use of dendrometers for determining how dry a crop feels for use in irrigation scheduling.

Case studies:

Sensor assisted Irrigation of Deciduous Orchards

Working with dendrometers and several other crop and soil sensors in an apple orchard in the Golan Heights, we disconnected several trees from irrigation in the summer and found that dendrometers were more sensitive to water stress than sap flow in the stem, which apparently adapted to drier soil for the first few days (Naor and Cohen, 2003). Later work focused on a protocol for irrigation with online sensors, using two types of soil-moisture sensors and dendrometers for stem contraction. The research, done in a nectarine orchard in the Golan Heights, showed that all three could be used and that stem contraction was extremely sensitive, but that during a phase of fruit growth when we could safely reduce irrigation, two of the three sensing techniques (including the dendrometers) exceeded their useful range (Nevo et al., 2015, Nevo, 2015).

Banana irrigation under screens:

Banana is a tropical grass, and grows well in the hot Jordan Valley, where it used to be irrigated extensively with water drawn from Lake Kinneret. In the 1960s, before the transition to drip irriga-

Figure 1. Sensors for measuring sap flow in pepper plants. The sensors were custom-built in Volcani's workshop.

Figure 2. Banana plants with sap flow sensors built in our lab (left). Calibration of the banana sensors in a greenhouse using a series of banana plants on electronic scales (right).

tion, bananas received about 5000 mm per year, or on average 14 liters per m2 per day. The transition to drip irrigation, along with a series of field experiments conducted over 15 years at the Zemah Experiment Station led by Yair Israeli, reduced the irrigation rates by about half in the late 1980s to 2700 mm. During a trip abroad, the researchers saw bananas grown in greenhouses, which improved fruit quality and plant performance. This led to a series of experiments that resulted in a transition to covering bananas with screens. At first, irrigation under the screens was the same as outside. But a project led by Josef Tanny in 2004-2007, which included measurements of climate parameters inside screenhouses and outside, along with measurements of crop water use with sap flow systems and agronomic monitoring by the staff at Zemah, showed that irrigation could be cut by another 25% and irrigation rates were set to less than 2000 mm.

Measuring banana water use with sap flow probes is especially challenging because the banana stem is different from that of trees and the sap flows deep inside. We built special probes for bananas, which are 15 cm long and are inserted carefully into the soft internal tissue that transports water at the base of the stem (see Figure 2).

Bananas are sensitive to salinity and Kinneret water is marginally saline. Experiments with better water quality, led by Dr. Avner Silber, showed that further cuts were possible, but the price of better water is prohibitive. Avner also noted that the relationship between irrigation below the nets and that outside should not be constant, because the build-up of dust on the nets in the summer should further reduce water requirements.

A current project of ours is monitoring climate inside and outside of the screenhouses and irrigating accordingly. Current technology allows the climate sensor data logging equipment to calculate the reference crop water use under the screen online and have that data ready for the irrigation manager through the internet every morning automatically. This "dynamic" irrigation has allowed a further reduction of 15% in irrigation rates, depending on which screen is used.

Over the past two years, the unscreened plantation received ↘

Figure 3. Sap flow sensors used in pine (left) and orchard trees (top right). The sensor assembly, built in our laboratory, is shown in the lower right.

Figure 4. Climate sensors deployed above a banana plantation for computing atmospheric "dryness" and irrigation requirements. These include standard high-quality solar radiation (left), air temperature and humidity (middle) and wind-speed sensors.

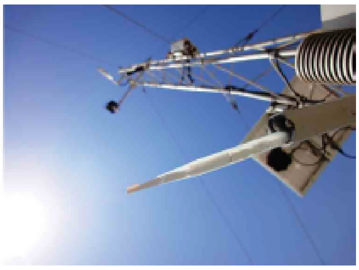

Figure 5. A minute "surface renewal" sensor (foreground in focus) for monitoring air parcels moving in the lower atmosphere. The sensor is mounted near the bottom of a meteorological mast with eddy covariance and energy balance equipment (background, out of focus).

→ 2200 mm, under the 10% screen using the recommended irrigation 1775 mm, and with dynamic sensor-based irrigation only 1465 mm, or less than a third of that in the 1960s. We are confident that the experiments will lead to adoption by the growers soon after completion of the project.

Water use of forest trees

Israel's water budget is tight and we use water frugally. We assume that rainwater percolating into the soil will refill our aquifers, from which we draw drinking water. A relevant question in managing natural systems, like our forests, is how much water they use and whether they use more than 'barren' land with no trees. If we are already asking that, perhaps we would like to know whether pine trees use more water than oak trees, and whether the aquifer would benefit from thinning our forests. These are questions that trouble forestry researchers in the department of natural resources (at the A.R.O.), in particular Dr. Yagil Osem and Dr. Gabi Schiller as well as Prof. Dan Yakir's group at the Weizmann Institute, who have long-term experiments monitoring the Jewish National Fund's Yattir Forest, east of Be'er Sheva' at the northern edge of the Negev Desert, and the Qedoshim Forest, near Bet Shemesh in the Judean Hills. With both groups, we have introduced networks to evaluate water use of forest trees using sap flow sensors. And yes, a pine tree forest uses almost all the rain water, leaving very little to percolate into the aquifer, while 'barren' land uses less. But it gives us a number of benefits (called ecosystem services) as compared to barren land, so we are forced to think carefully about planting forests and their associated cost/benefits.

CONCLUSIONS

Current technological advances in electronics and wireless and internet communications are making sensing technologies attractive due to their relatively low cost and effectiveness, and long-term monitoring in the field is becoming more common. Our team has been successful in developing, adapting and implementing a group of technologies for monitoring climate and crop water use and evaluating climate "dryness" for plants. These sensing technologies are important for irrigation scheduling. They have helped us develop irrigation strategies for orchard crops as well as crops grown under screens, including peppers and bananas. In the case of bananas under screens, a series of projects has led to large reductions in irrigation and concomitant savings in water. ❑

FURTHER READING

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