ADVANCES IN MICROIRRIGATION CONTROL BY SAP-FLOW MONITORING SYSTEMS

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ABSTRACT

Over the last seven years, new advances in the techniques for sap-flow measurement have made the measurement of water use in crops, trees and vines a simpler and more economical process. A new system design is explained and a new microirrigation controller implementation is proposed in this paper. The method has been studied, and research has proven the utility of the heat balance sensor method of determining transpiration (T) and how it relates to sap flow (F). Many crops have been measured in the field under realistic conditions, and studies are proving the utility of the method in a variety of applications of stem gauge, a sensor produced with the heat balance theory. Citrus and fruit growing applications have recently been explored and are shown to be useful in determining water stress and in relating water consumed to the amount of hourly or daily evapotranspiration (ET) demand. Two new sap flow monitoring systems have been recently produced which are being adapted for the closed loop, automatic control of water valve timing needed to keep crop production at a peak, while minimizing water use and preventing water stress. Although many more species need to be tested using stem-flow technology, many of the principal economic crops of the world have been shown to be effectively monitored using stem gauges.

Keywords: Sap flow measurement, heat balance, in situ, microirrigation, microcomputer control, water stress

SAP-FLOW MEASUREMENT OVERVIEW

By measuring sap flow directly with a simple and accurate means, the ageless question of how much water does a plant need to be healthy and produce up to its full potential can be answered directly. The heat balance method applies the principles of thermodynamics, heat transfer, and conservation of energy to determine the amount of heat and mass flow of water moving up the stem. In Baker and van Bavel/(1987), the method of sap flow sensing was developed indicating that it was possible to produce a fully portable sensor which required no calibration, and was non-invasive nor harmful to the plant stem.

Constant Heat - Energy Balance Method

Sensors from 5mm to 125 mm stem diameter, incorporating the stem heat balance method, are manufactured by Dynamax Inc, Houston, Texas. The heating power to an annular heater strip on the stem is adjustable, and may be modulated from time to time to maintain temperatures within practical limits. The energy balance principle based on the conservation of energy determines the heat absorbed by the sap:

$$Qf = Qin - Qr - Qv \quad (W) \qquad (1)$$

By measuring the power input to the stem by the heater strip (Qin), the vertical heat loss by conduction (Qv), and the radial heat loss (Qr), the remainder is convection heat from carried by the sap (Qf). The patented four-channel design of the Dynagage sap flow sensor (Fig. 1) contains temperature sensors that are placed around the heater strip measuring Qr, the heater voltage senses wires measure Qin, and temperature sensors above and

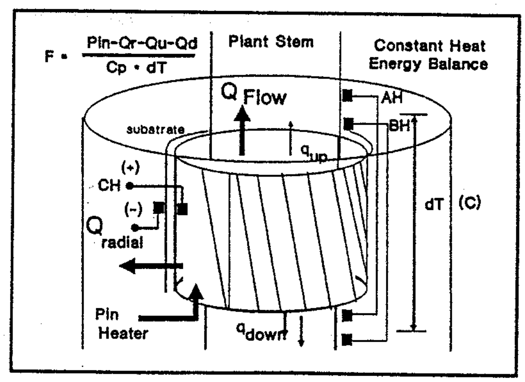

Figure 1. Stem Flow Gauge Schematic

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below the heater strip measure Qv and the dT temperature increase of the sap. Qf is the remainder of the heat balance, the heat convection carried by the sap. After dividing by the heat capacity of water (Cp) and the temperature increase, (dT), the heat flux is converted directly to mass flow rate.

$$F = (Qf) / Cp * dT \ (g/s) \quad (2)$$

Citrus and Fruit Growing Applications

In tests performed on grape vines, peach and pecan trees in Texas, there are several good examples of relating water use to the environmental conditions and studying the plant response to various water conditions. In addition it is shown that in a low water usage crop such as grape vines, flood-irrigated fields can lose up to 75% of the water to evaporation.

In the example shown in Fig. 2, apple tree water consumption is traced for the day. The short term effect of clouds and a rain period at 12:00 are easily shown. The clear advantage of this data is a real time evaluation of the water consumed by the crop, equal to 1.7 liters per plant. This example is a three year old tree of the Granny Smith variety planted in trellised rows (2.5m high and 36mm diameter at the base). The proposed irrigation system can be programmed to replenish the water consumed reflecting the seasonal and daily changes by the environment as well as the growth of the trees.

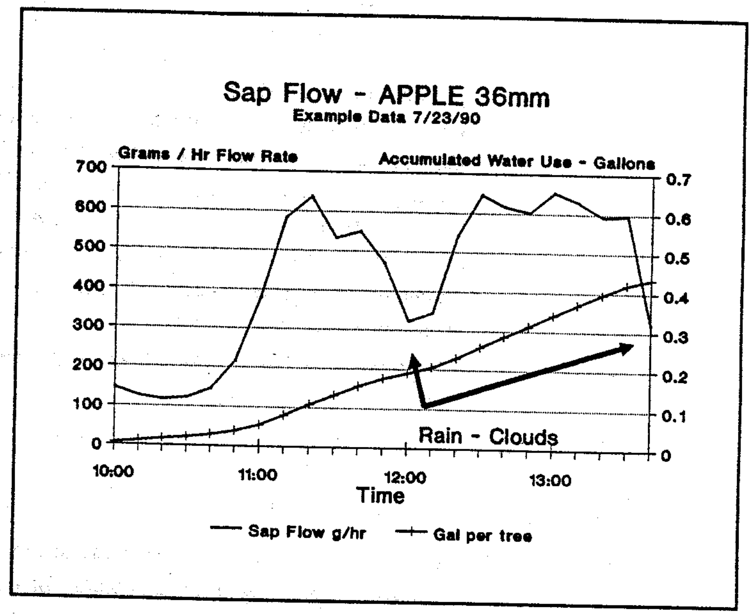

Figure 2. Typical Sap Flow and Accumulated Water Use

In a lysimeter study, peach trees 5 m high and with a canopy of 5 m were monitored by the SGA100-ws, a stem gauge with a trunk capacity of 100 to 125 mm diameter. Shown in Fig. 3 are three days comparison between a covered lysimeter and the stem flow gauge. The total consumption was 210 kg using the gauge and 235 kg by the lysimeter. Over three days the sap flow was within about 11%. (Van Bavel, 1992)

A recent study on Chardonnay grape plants by Lascano (1992) evaluated the utility of stem gauges and to determine the efficiency of furrow irrigation on a crop about which little is known regarding its water us-

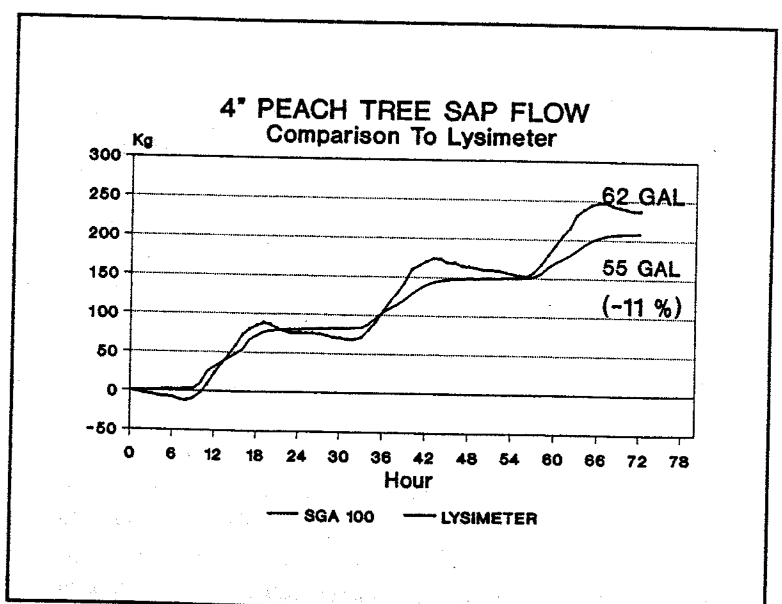

Figure 3. Peach Tree Sap Flow Measurement vs. Lysimeter

age. When results were published from the 100 day experiment on grape vines (*Vitis vinefera*) showing the total ET from an irrigated field, and compared to the total sap flow from the grape vines, it was discovered that 77% of the ET was due to soil evaporation. Potted plants were confirmed to have sap flow and gravimetric water loss within 5-10% of each other. This study also showed the utility of normalizing the results of the test plant's sap flow by the leaf area to determine the total water transpired for a given acreage. This method greatly reduces the variability of the data.

Crops Research and Results

Over the last several years Dugas (1990), Heilman(1990), Ham (1991), Howell (1991), Saliendra (1991), and Guiterrez (1994) have shown the effectiveness of sap flow measurement on cotton, maize, sorghum, sugarcane and coffee. A comparison of the stem flow gauge with a lysimeter on cotton plants (Dugas 1990) showed that the method was accurate for cotton plants (error <+/-10%); however the amount of sap flow varied widely between plants. The coefficient of variation increased as the season progressed, as the sizes of the plants varied more. Later it was shown by Heilman (1990) that by indexing to the leaf area, in the case of Ligustrum, the variation in water use, indexed by leaf area, between plants is negligible as long as the exposure is the same. A later publication by Ham (1991) proved that this was also the case for cotton. The clear implication is that determination of the crop water use by a number of plants tested for sap flow should be indexed to the main crop not by the number of plants, but instead the leaf area of the tested plants to the leaf area of the total crop.

CLOSED LOOP MICROIRRIGATION CONTROL SYSTEM

In this control method, the continuous scanning of the water transpired, and the ability of the pump controller to deliver a matching amount of water, provide a closed loop from the plant to the sensor, through the sap flow system, to the pump controller, through the water delivery system back to the plant (Fig 4).

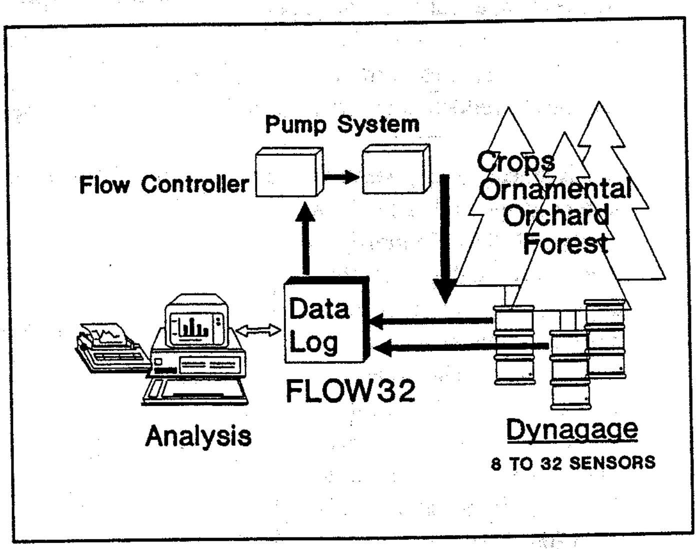

Figure 4. Closed Loop Microirrigation Controller System Design

The Flow32 system is now available to measure the sap flow in the field for eight to 32 plants simultaneously. Flow32 integrates all of the logging, storage, retrieval, and power functions into a complete package (See Fig. 5). IBM PC portables or compatibles are the best choice to load programs and to run formatting or retrieval utilities. The system includes multiplexers, assembled and tested wiring, a solar panel or 120V power supply, voltage regulators, retrieval cables, data storage modules, and weather proof enclosures. Each Flow32 not only includes all of these functions, but also incorporates real-time graphics monitoring.

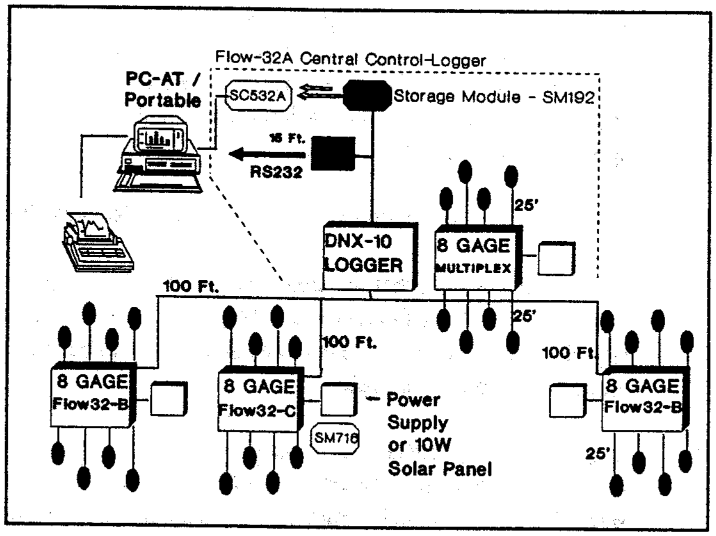

Figure 5. Typical Flow32 Sap Flow Monitoring System Schematic

Most importantly, the system can be programmed to add the microirrigation control function. When the system detects a fixed volume of water consumed per plant, an internal comparison of the fixed set point is programmed to signal the irrigation pump logic to replace the water used.

For an illustration, let us assume that a crop is to be irrigated by one l/hr emitters, one emitter per plant, and tied into a typical timing based irrigation controller and pump installation. The irrigation controllers are usually programmed by microprocessor to handle a certain schedule of water delivery at certain hours, for a fixed length of time. In this system the program is changed to deliver one liter, or turn on the pumps for one hour, upon demand of a control signal. The irrigation controller is therefore variably initiated at demand of the plant instead of a preconceived "feeding schedule". A fixed time span for the duration of its pumping time simplifies the installation of the irrigation controller.

For this example, the system is programmed to pulse a relay upon reaching an accumulated water transpired of one liter (less any rainfall). When the volume transpired equals the Tc set point of one liter., a pulse to the irrigation controller is sent for opening the water valves for one hour. If multiple pulses are received, the irrigation controller will accumulate additional hours of pumping for each zone in use, until all plants have received the full allocation of water. Under very high ET demand, and when a irrigation system running at full capacity at the peak of the growing cycle, the system pumps will run more time at night to catch up from the accumulated water use during the day.

The system adds the plants water use in the sample and indexes by each plant by leaf area (A1...n), a constant input by the user. For example:

$$Tc = ((T1/A1 + T2/A2 + T3/A3 \ldots Tn/An) \;/ N)*(Ac) \qquad (3)$$

Tc is the transpired water for the typical crop plant, or crop area covered by one emitter. The number (N) of the plants where T is monitored by sap flow sensors could be as small as 2-5 plants per zone when a small area is controlled, or may need to be 5-8 samples when the area of controlled irrigation is very large. The total area of the crop (Ac) can factor the water applied to a large number of plants covered by a single emitter or delivery zone. In this general form, the crop area, Ac can be computed from the leaf area index. T1...Tn are readings provided directly from the stem gages, taken every minute, averaged, and accumulated hourly in grams/hour. The accumulated mass flow of water is converted to the volume measurement units of the water delivery system.

Two basic options are available depending on the expected rainfall. First, if the system is inside a cover, or a greenhouse, there is a version of the system with no ability to adjust for rainfall. If the system design applies to a crop where rainfall is expected to provide a significant amount of the water needs, an electronic rain gauge attached to the system measures the rainfall, is indexed by the plant canopy area, and subtracted from the water applied to the plants by irrigation.

$$\text{Tc accumulated} = \text{Tc actual} - \text{Rainfall (Rain efficiency, Volumetric)} \quad (4)$$

We should be aware that the area of the crop will change dramatically with the growth of the annual crops, however the ratio of (Ac/A1+A2...AN)/N is dimensionless, and should be adjusted when the LAI changes significantly. Therefore the A1...An, and Ac would be prudently updated weekly during leaf emergence on crops, and annually on trees.

This new control method is designed to be simple, and in theory foolproof. The sap flow microirrigation method will provide a simpler measurement method and a more accurate measurement than meteorological stations with ET models. Further, labor intensive soil moisture methods of scheduling irrigation can be cut back to a relatively easy monitoring of soil saturation, and the soil moisture level at the projected start of the planting period on crops.

SUMMARY

The closed loop feedback system which determines the application of water from the actual plant use will have the greatest accuracy and therefore yield improvements, with greatest water use efficiency. The system design described herein will connect the demand from the plant directly to the delivery of water. Seasonal weather and fertigation related variations in water demand are precisely determined for real-time systems, and will provide the fundamental water delivery requirements as well as cost savings in future crop production by microirrigation systems.

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