WATER & IRRIGATION REVIEW

System solutions for real-time sap flow monitoring

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Basics of Sap-Flow Measurement

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 use of an energy balance method uses 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-van Bavel (1987), the most recent 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. Sap flow was measured in the stem of small (<16mm diameter) herbaceous plants. On larger, woody species from 35mm to 45mm diameter, the stem heat balance was successfully tested on Ficus Retusa and Ficus Benjamina ornamental trees, (Steinberg (1988) and Steinberg-van Bavel (1989)).

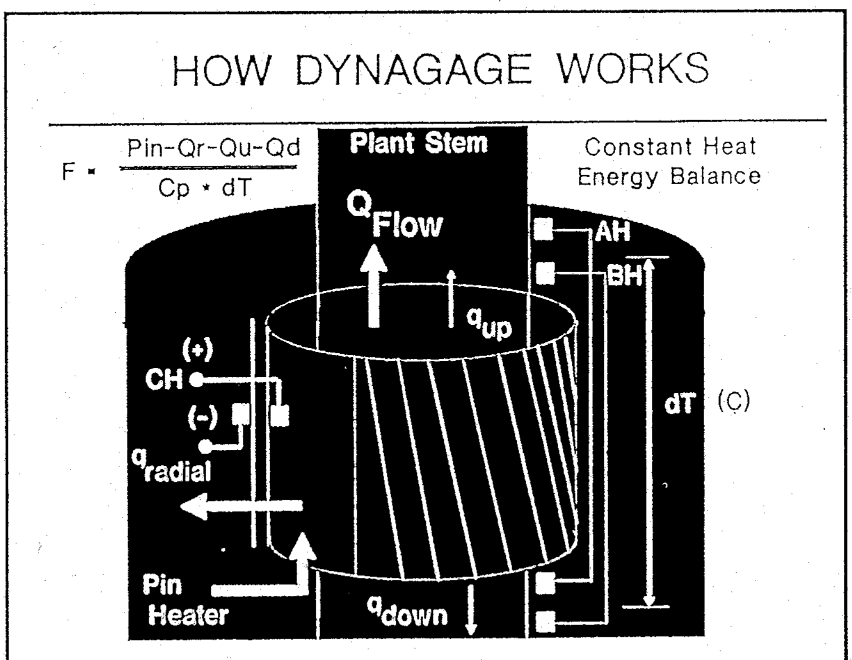

Figure 1 - SHB Sensor Schematic

Constant Heat - Energy Balance Method

A stem heat balance method that uses a constant power input to the heater is manufactured by Dynamax Inc., Houston Texas. A strip heater within the gauge inputs energy to the stem at a constant rate, Qin. The energy balance is the principle based on the conservation of energy that determines the partitioning of energy to the stem, the sap flow (Qf) and the heat losses to the ambient:

$$Qin = Qf + Qv + Qr + Qs$$

Where Qin is the constant heat applied in watts, Qf is the heat flux energy carried by the sap flow, Qv is the heat

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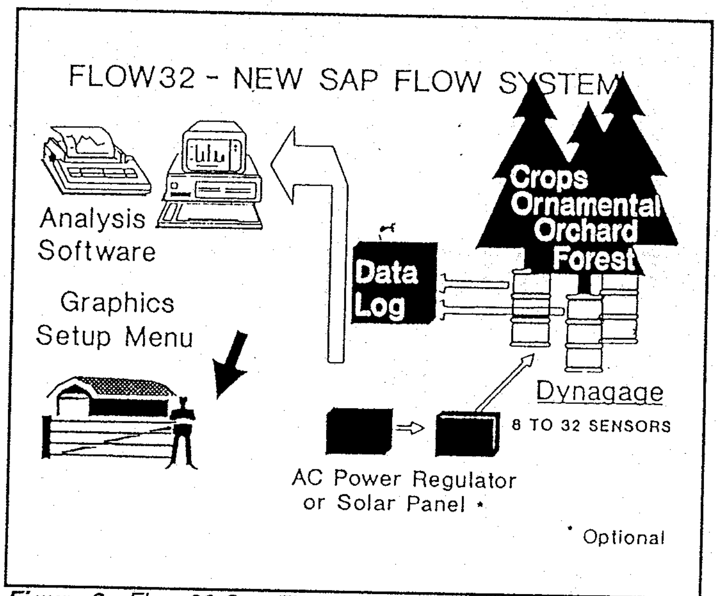

Figure 2 - Flow 32 Sap Flow System

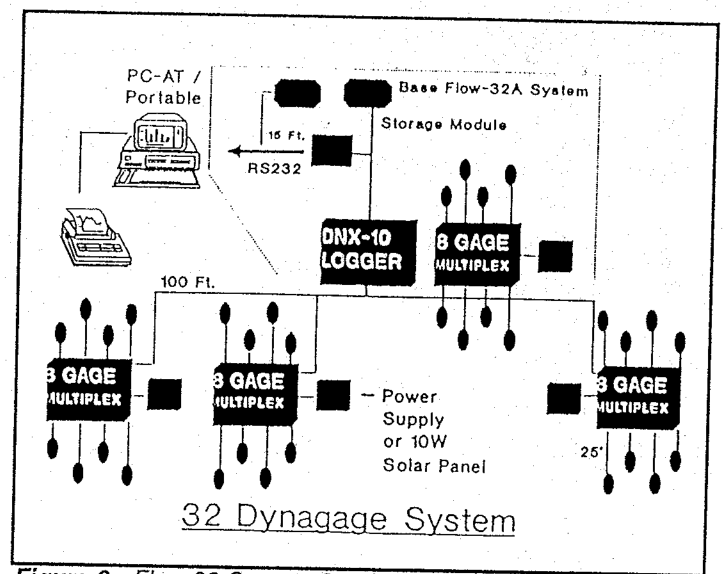

Figure 3 - Flow 32 System Configuration and Expansion Options

conducted up (qu) and down (qd) the stem axially, Qr is the heat conducted through the insulation radially to the ambient, and Qs is the heat stored in the stem test section. For most applications Qs is assumed to be small and can be ignored for all but very low sap flow applications. By measuring Qin, Qu, Qd, and Qr, the remainder, Qf can be calculated. Qf is the heat convection carried by the sap. After dividing by the heat capacity of water and the temperature increase, the heat flux is converted directly to mass flow rate.

Systems for Monitoring Sap Flow

Since the development of the original portable prototypes, Dynamax has developed commercial versions with weather proofing, rugged internal electronics, and installation methods that make the sensor easy to remove and repeat usage on new plants or locations. Each gauge directly measures sap flow easily and inexpensively. The non-invasive sensor design means there is no harm to the plant. Since the sensor is flexible it conforms to the shape of the stem and accommodates growth up to 30%. The constant heat method is reliable, and the proven energy balance assures the low occurrence of problems getting good data. Since real time measurements are possible and there is a relatively low time constant, decision making is current. In support of all these benefits and advantages, to easily use these advanced sensors in large numbers, and to interpret the real time information expeditiously, the Flow32 system was developed.

With the development of complete systems and standardized software, the detailed implementation of the energy balance equations in the previous section is transparent to the user.

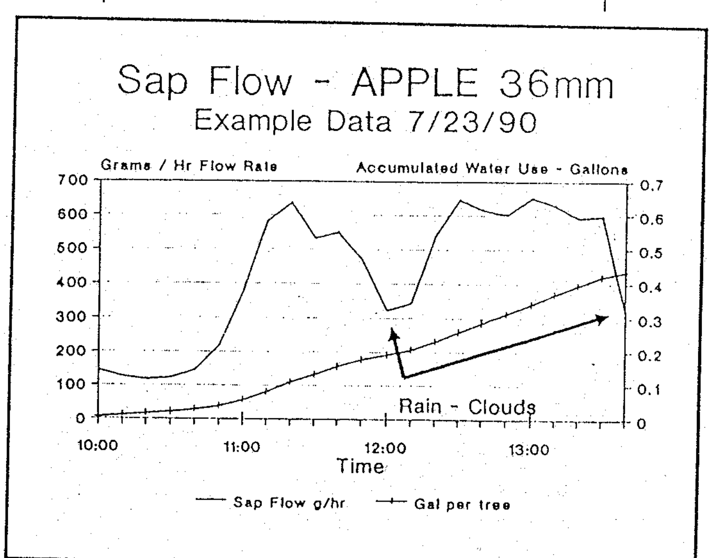

Figure 4- Apple Tree Sap Flow Example

Citrus and Fruit Growing Applications

In tests performed on grapevines, 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 over 75% of the water to evaporation.

In the example shown in Figure 4, water consumption is tracked for the day. The short

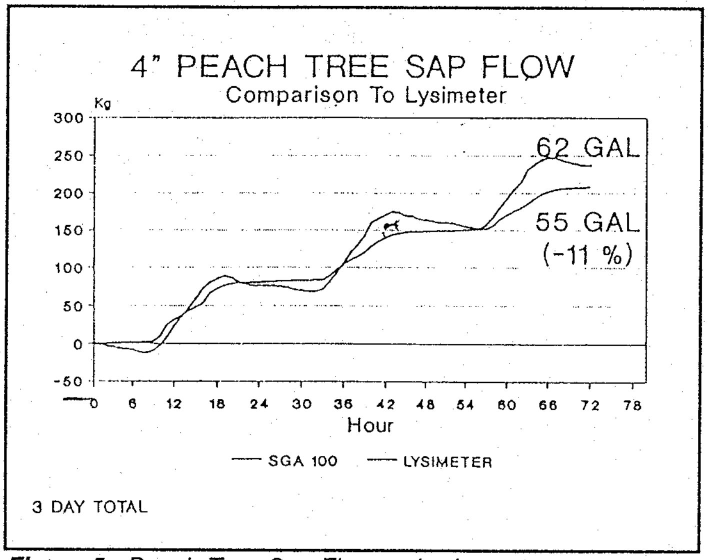

Figure 5 - *Peach Tree Sap Flow vs Lysimeter*

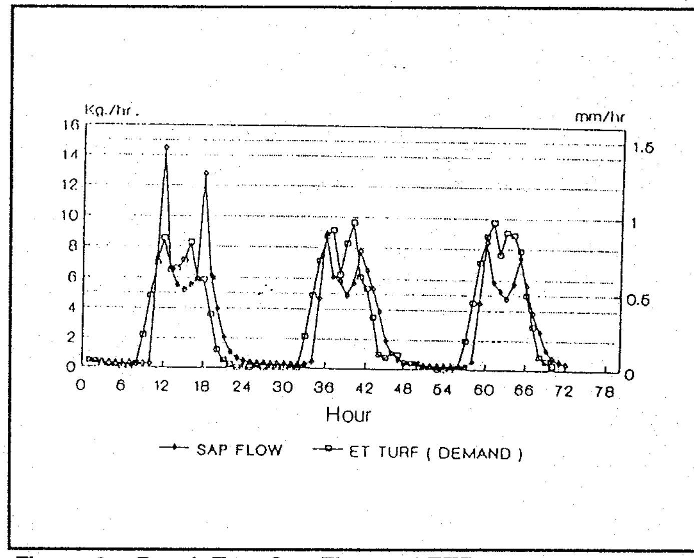

Figure 6 - *Peach Tree Sap Flow and ETP*

term effect of clouds and a rain period at 12:00 is easily shown. Note that the sap flow did not come to a total stop for two possible reasons: 1) there is still sunlight coming through the clouds, and 2) the sap flow continues to replenish the water lost by transpiration at the leaves. Typically there is a lag of 30 minutes to an hour between the transpiration and the total sap flow. The clear advantage of this data is a real time evaluation of the water consumed by the crop, equal to 0.44 gallons per plant. This example was taken in a three year old tree of the Granny Smith variety planted in trellised rows (2.5m high and 36mm diameter at the base). The 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.

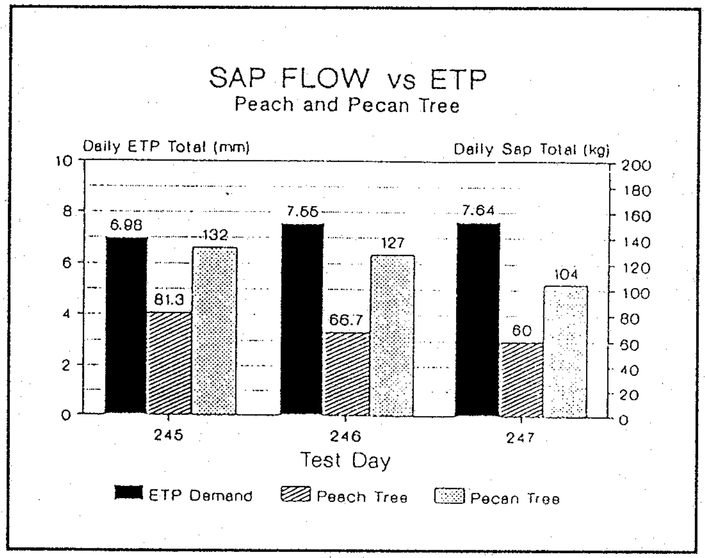

Figure 7 - *Peach and Pecan Tree Stress*

In a lysimeter study, peach trees 5m high and with a canopy of 5m were monitored by the SGA100-ws, a Dynagage with a trunk capacity of 100 to 125mm diameter. Shown in Figure 5 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 4% per day, for a total variance of about 11%. As one can see in the evening data, lysimeters are subject to temperature changes, wind stress changes and drift in measurements.

With respect to the application of sap flow measurement to detect water stress, an index of comparison is the ETP computation, or evapotranspiration demand computed from radiation, wind speed, humidity, and air temperature. Dynamax supplies a weather station and preprogrammed software, Penman-van Bavel, to collect and interpret this data. By charting the sap flow rates along with the hourly ETP (in mm/hr), Figure 6 shows the close fit of the sap flow to the demand especially when well watered on the first of three days. Upon close inspection, one notes the demand always leads the sap flow. The bar chart in Figure 7 shows the accumulated ETP for three days with the water consumed by the same peach tree as in Figure 6 along with an adjacent Pecan tree. Both trees were well watered on the first day and not watered for the next two days. Since an enclosed lysimeter has a fixed amount of water available, stress is evident by the third day. With the weather conditions indicating a 9.5% increase in demand for water, the peach tree water use was down to 74%, and the pecan tree was down to 78% of the well watered sap flow. By the third day, there is a noticeable slump in the sap

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flow caused by a more limited availability of water. Studies of this type can also be done in place in the orchard by simply keeping one set of trees in good supply of water, measuring total flow (Ftw), replenishing all that is used, and comparing this to the normal field trees (Fts) of similar size and exposure, and establishing the stress index of:

Fts/Ftw = water stress index

expressed as a ratio of the total sap flow of stressed trees to those that are not stressed.

A recent study of Chardonnay grape plants by Lascano (1992) began last year to evaluate the utility of stem gauges and to determine the efficiency of furrow irrigation on a crop about which little is known regarding its water usage. 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. The ET total was confirmed by neutron probe measurements which were correlated to rainfall and irrigation data, and the T was measured by Dynagages. 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.

Crop Research and Results

Studies have shown the effectiveness of sap flow measurement to study cotton, maize, sorghum and sugarcane. Many additional research projects were presented on the utility of sap flow determination of transpiration in a recent Sap Flow Symposium in the American Society of Agronomy, October 1991.

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, at least in the case of Ligustrum, the variation in water use between plants is negligible as long as the exposure is the same. A later publication by Ham (1990) proved that this was also the case of 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.

Ham (1991) also separated E from T in a cotton crop using the Bowen Ratio-Stem Flow method. Never performed in this way before, the total ET was determined with the Bowen Ratio method, and T was independently monitored by sap flow gauges.The E was independently checked by microlysimeters. On the average E calculated was within 11% of measured E. Other researchers were successful in performing the same analysis on corn and soybean.

Saliendra (1991) prepared a stem flow driven analysis of three sugarcane (Saccharum) genotypes to look at stomatal conductance and root hydraulic conductance particularly during soil drying. Saliendra found that the genotypes all varied in transpiration at all stages of soil drying. However the conductance: transpiration had a linear relationship for all types. This suggested that liquid water transport efficiency regulates the water vapor loss.

Horticulture Applications

Recently two unique examples of the advanced research made possible by Dynagage were published. Steinberg and Zajicek(1991) were able to determine accurately the effects of chemical growth regulation in comparison to pruning on Hibiscus (Hibiscus rosa-sinensis L). The study showed that chemically treated plants used 33% less water than control plants, and that pruned plants used less water initially, but after regrowth, the usage was only 6% less than control, after the end of the 50 day test. Peak flow rates were also affected dramatically on a leaf area basis. For example sap flow was 120 to 160 g*h-1* m-2 on the pruned and control plants, nearly three times higher than the 40 to $70g{*}h^{-1}{*}m^{-2}$ on the chemically treated plants.

Another example of a similar study by Steinberg and Zajicek (1991) on Ligustrum Japonicum showed the short term effects of growth reduction treatments. In this instance, with a clear contrast to the Hibiscus, growth retardants did not change the flow rate per unit leaf area, but did have a impact on water relations through the decrease in leaf area of the plants. More studies of this nature are planned to relate water use characteristics to the physiology of the plants and the effects of growth regulation.

Summary

In the future more horticulturalists, soil and crop scientists, agronomy, patholology and environmental researchers will be able to make use of the new sap flow technology with much greater ease using Dynagage and the fully integrated Flow32 Systems.

Agricultural engineers in arid lands can efficiently design drip and sprinkler irrigation systems with sap flow information. 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. Seasonal and weather related variations in water demand are precisely determined for real-time systems, and may provide the fundamental water delivery requirements without resorting to an over design and related extra expense in future systems.

Water management, hydrology, and water quality studies now have the tools to separate water flux into transpiration from the plants vs soil evaporation and leaching. The sap flow information on stream bank vegetation, phreatophytes, and range land invaders such as mesquite and cedar trees, provides the user with the water flux data that is essentially unavailable from other sources. The health of a plant may also be monitored by observing the sap flow. Root damages, insect damage and competition with weeds can be quantified and compared to healthy plants, or by observation of the crop over time. Air quality is an increasing area of concern. The effect of pollutants on the process of photosynthesis and transpiration are indirectly measured via sap flow instrumentation, as long as plants can be isolated from the pollution to provide a benchmark against plants in polluted air. The effects of treatments to counter cell destruction by pollution in either the groundwater or the air may be established clearly with monitoring by Dynagage.

The use of Dynagage to observe genetic engineered plants for resistance to drought, growth patterns, and fertilizer efficiency are new applications having great benefit to the farming industry.

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