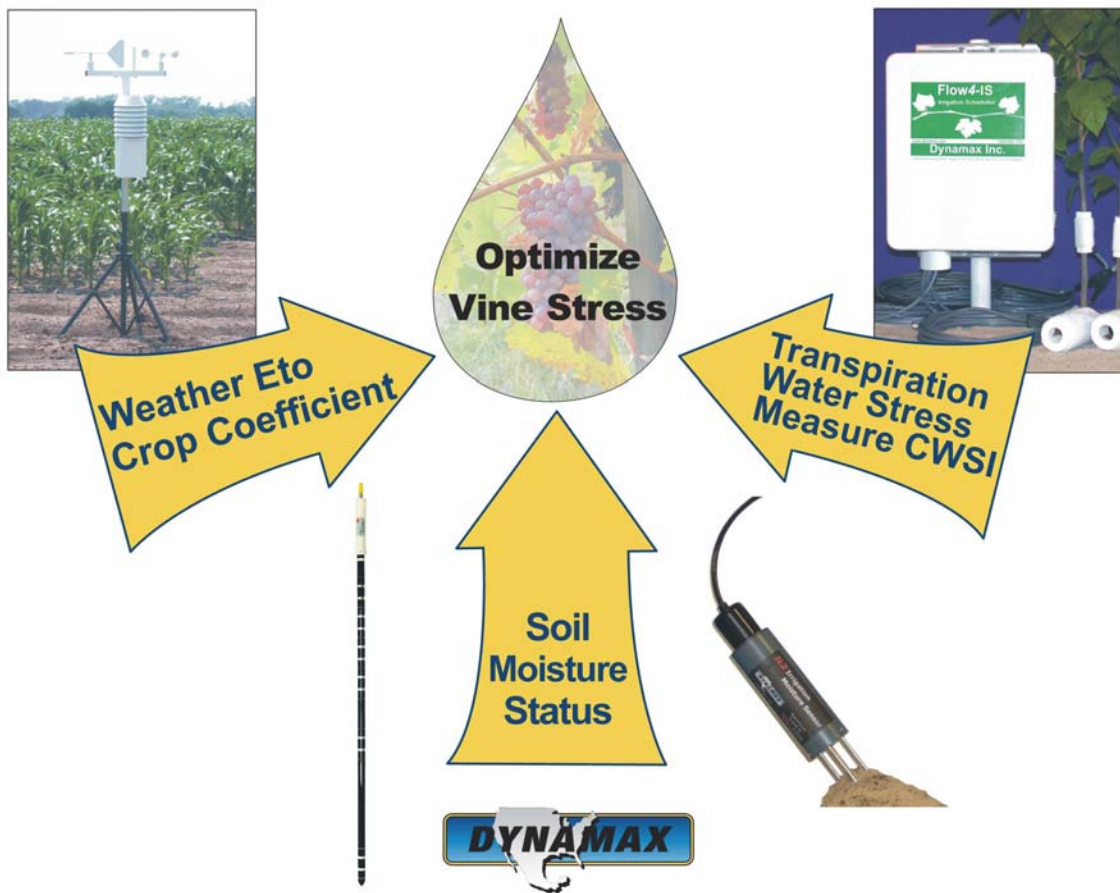


**Unified Wine and Grape Symposium Poster Presentation,
Sacramento California**

Vine Stress Monitoring



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Vine Sap Flow Stress Measurement

Objectives:

- **Transpiration measurement method – Collect data to measure Crop Water Stress Index using the sap flow method.**
- **If there is sufficient data, show the average crop stress, and irrigation deficit.**
- **How does irrigation deficit and crop stress compare, and is it controllable?**
- **Feasibility analysis of utilizing Sap Flow for irrigation control in test / field conditions.**
- **Yield and crop quality analysis compared to Sap Flow data / CWSI stress results.**

2003 Sap Flow CWSI

Background:

Initially transpiration stress measurement was proposed in the 1992 National Irrigation Convention Proceedings (**Van Bavel, Michael G.** 1992, Stem Flow Gauges for Measurement of Crop Water Use, National Irrigation Convention Proceedings, (pg 59-72) and published in International Water & Irrigation Review (**Van Bavel, Michael G.**, 1993, System Solution for Real-Time Sap Flow Monitoring. International Water & Irrigation Review, Vol. 13, No. 1, 1993, pp.25-29.) In 1992 **Lascano** (Am. J. Enol. Vitic. Vol 43: (2)) published water use records on grapevines and confirmed the accuracy of the stem heat balance method.

In 1995 a closed loop method of controlling irrigation by a sap-flow monitoring system was proposed (**Van Bavel, M.G., 1995** - Advances in microirrigation control by sap-flow monitoring systems. Proceedings of the Fifth International Microirrigation Congress., ASAE., April 2-6, 1995, Orlando, Florida: 234-238). An integrated sap flow, ET weather station network, and transpiration modeling approach was described in 1996 by a Texas A&M study by Dr. Robert Lascano (**van Bavel, Cornelius, H.M., van Bavel, Michael G., Lascano, Robert, J., 1996** - Automatic Irrigation Based on Monitoring Plant Transpiration. American Society of Ag Engineers, Proceeding of the International Conference Nov 3-6, 1996, pp 1088-1092.)

After many years in development and testing, in November 2002 the closed loop method was implemented by Dynamax Inc with the announcement of the FLOW4-IS Irrigation Scheduling system (Pat pending). This study is the first case of the system operation being documented in a water stress measurement application. The cooperation and support of Robert Mondavi and Neil Roberts, Central Coast Grower Relations, for the use of the Cuesta Ridge Vineyard, and assistance in the testing was greatly appreciated.

Study outline –

**Cuesta Ridge
Vinyard, Robert
Mondavi**

**Sap flow sensors – 4
SGB25 installed in
rows as shown.**

**Soil moisture sensor
ML2- ThetaProbe at
logger 18 inch deep
next to a vine.**

**ET provided by
nearest CIMIS
network station.**



**Installation and training
provided by Dynamax Aug 13
2003.**

Transpiration - Sap Flow Measurements

Transpiration measurement method -

- Dedicated data logger – Flow4
- Four sap flow sensors with Dynagage heat balance method
- Solar power – batteries installed
- Soil Moisture Sensor – ThetaProbe
- Input Parameters for vineyard into Flow4 processor
 - Plant Density
 - Area
 - Irrigation efficiency %
 - Evaporation %
 - Stem area (or leaf area)
 - Field stem average area (or leaf area index)



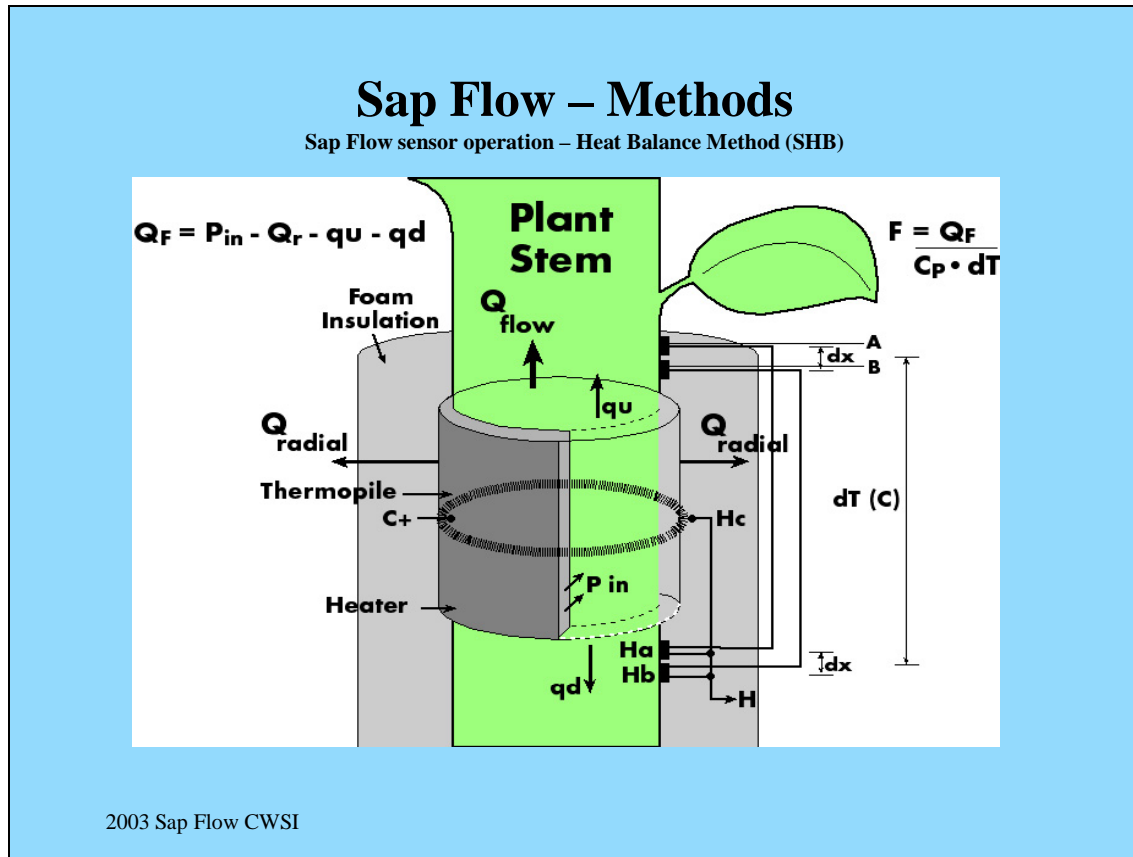
Options for automatic water balance were not used in this study:

- Tipping Bucket Rain gage - rainfall is not a factor in this area.
- Flow Meter – irrigation applied, however was recorded manually.
- Valve Control – scheduled by water deficit, days for irrigation. Valves were operated by timer in this study and adjusted by vineyards manager.

2003 Sap Flow CWSI

There are two approaches possible for sap flow transpiration stress measurement. One approach would be to compare sap flow by set of well-watered plants with a set of plants in stressed conditions. This method requires two sets of plants and two independent records of sap flow, but could be performed without a weather station reference ETo.

The alternative explored in this study is to measure sap flow after irrigation when well watered, and then compare the sap flow on the same set of plants during stressed conditions. A benchmark crop coefficient (K_c) is then established in actual field conditions. The maximum transpiration can be calculated and compared to the actual transpiration for subsequent conditions of stress. This approach requires a weather station reference ETo, but only one set of sap flow readings.



The heater surrounding the stem applies a constant heat (P_{in}) to the sapwood. The resulting heat flux loss in the radial (Q_r) and vertical direction ($Q_u + Q_d$) are measured with a thermopile and a series of thermocouples. The convective heat absorbed by the sap flow, and therefore the rate of water flux along the stem can be calculated by subtraction from the heat supplied. The temperature difference above the heater from the ambient sap temperature converts the heat to the mass of water flowing per time unit. Simply, the faster the sap flows up the more it cools the sensor heater. The energy balance measurement does not require calibration.

$$F = (P_{in} - Q_v - Q_r) / C_p \cdot dT$$

Where:

F = Flow rate per unit of time

P_{in} = Power supplied in watts

Q_v = Vertical or Axial conduction

Q_r = Radial heat Conduction

C_p = Specific heat of water (4.186 J/g°C)

dT = Temperature increase in sap

Sap Flow Sensor Method



- **Sensor installation:**
- **Sensor with heater wraps all around the stem.**
- **Sensor insulated from radiation, stem insulated below and above sensor.**
- **Sap flow sensor measures heat absorbed and temperature rise. Then logger converts results to mass flow.**
- **4 sensors automatically indexed for vine stem-size to the crop average.**
- **Sap flow results saved hourly and accumulated daily.**
- **Sap flow is converted to mm water used in Flow4.**



2003 Sap Flow CWSI

Sensor installation is shown here. Contact with the stem, and sapwood is important for good results. Loose bark and rough spots on the stem are removed and smoothed with sand paper. Temperature sensor points are placed in good contact with the surface of the stem, and the heater completely surrounds the stem. To prevent stem temperature gradients and sunshine on the stem, all parts of the stem are protected and shielded with weather shielding, an aluminum bubble shield provided with the sensor. Additional shielding above the sensor was needed to prevent solar heating at the cordons juncture with the main stem. The sap flow sensor is mounted about 3/4 m above the ground. These methods ensured the heat transfer and measurement are not disturbed by external factors in accordance with the manufacturer's instructions, and many published papers on the subject.

Sap Flow Water Stress Theory

1) Perform comparison from demand E_{To} to actual water transpired – under well watered conditions.

- **Determine the actual Crop Coefficient (K_c) on site**
- **Measure Sap Flow continuously (E_{Ta}), record maximum daily transpiration relative to E_{To} , (E_{Tm}). Data may be converted to mm water used.**
- **Record E_{To} from automatic weather station.**
- **Compute :**

$$K_c = E_{Tm} / E_{To} \quad (\text{mm/mm})$$

During well watered conditions, day after thorough irrigation. (Idso, 1982)

2) Compute the transpiration stress index during any subsequent day by:

$$CWSI = 1 - E_{Ta} / E_{Tm} \quad (\text{Idso, 1982, Jackson et. Al. 1981})$$

E_{Ta} = Actual transpiration; $E_{Tm} = E_{Tww}$ - maximum transpiration projected by weather condition.

$$E_{Tm} = K_c * E_{To}$$

Ex: $CWSI = 0$ ~ no transpiration stress.

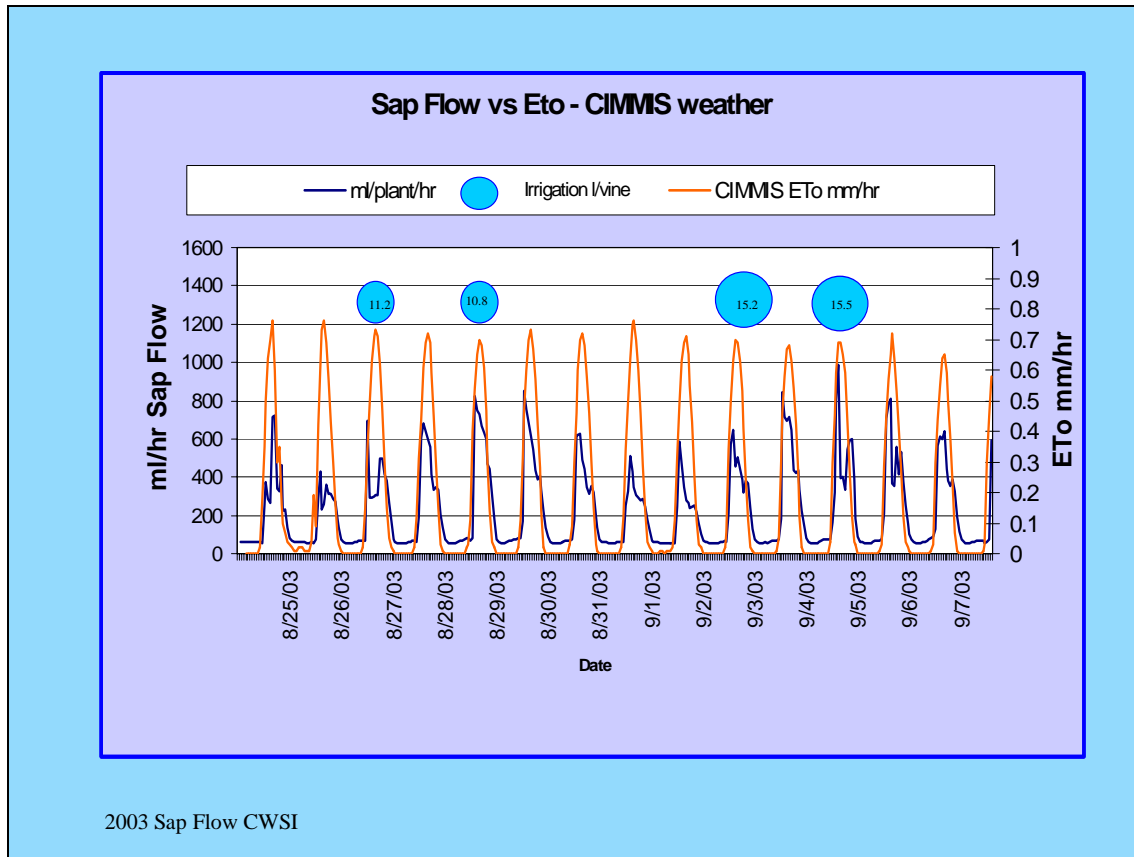
Ex: $CWSI = .5$ ~ means transpiration is 50% of the maximum well watered condition.

3) With evapotranspiration records, summed daily, stress is observed in progress after irrigations.

2003 Sap Flow CWSI

The method of Crop Water Stress Index was developed in the early 80's for crop yield improvement in Arizona,. Idso, Jackson, and Reginato defined the Transpiration Stress Index as a strong indicator of crop yield. As transpiration declined due to water stress, the yield was reduced. The CWSI became a commonly used term when they developed the canopy temperature measurement means for detecting crop water stress. As temperature increased relative to air temperature, the transpiration is reduced by stomata closure. Under these circumstances photosynthesis is reduced and the crop "shuts down" due to water stress.

In this new method and definition, direct transpiration readings from whole plants replace the indirect computations of canopy temperature, air, and VPD. By detecting stress through the sap flow method, it is hoped that inherent difficulties of canopy leaf measurements are avoided, yet the strength of the CWSI indexing method becomes readily available to growers.

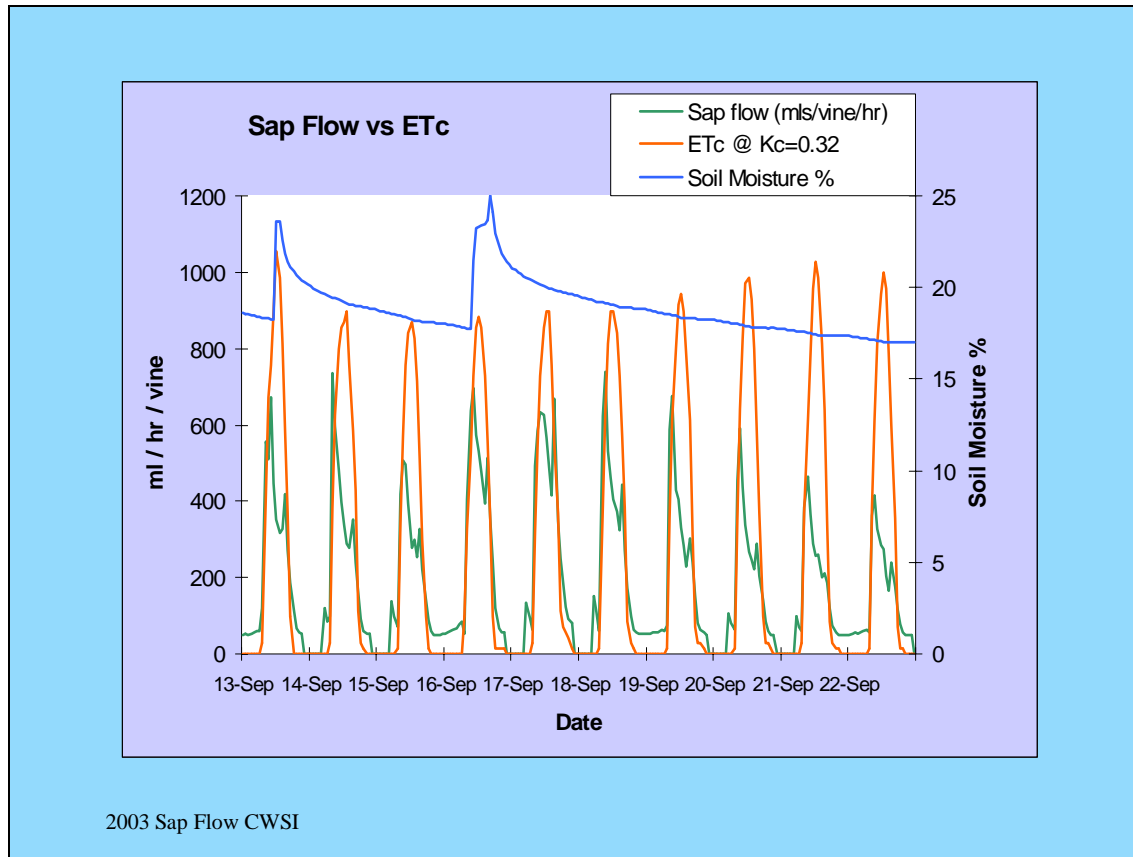


2003 Sap Flow CWSI

The results here show the first two steps in determining the Crop Water Stress. First the Sap flow must be recorded hourly with heat balance sensors that compute sap flow in grams or ml per hour. Fourteen representative days from late August are shown here, with sap flow in blue. The sap flow record includes all four sensors with a weighted average, weighted by stem size. The sensors were installed on stems that were of average size. Flow4 software automatically throws out one outlier of the four readings to improve reliability of the readings and adjusts the average sap flow by the stem size of each plant and then indexes sap flow to the average crop stem size. The Flow4 automatically calculates the mean based on stem cross-section area, and may also employ leaf area as the index.

In this data from late August to Sept 7, the ETo is shown in mm/hr (right scale), and sap flow is shown in ml/hr (left scale).

Slide 8

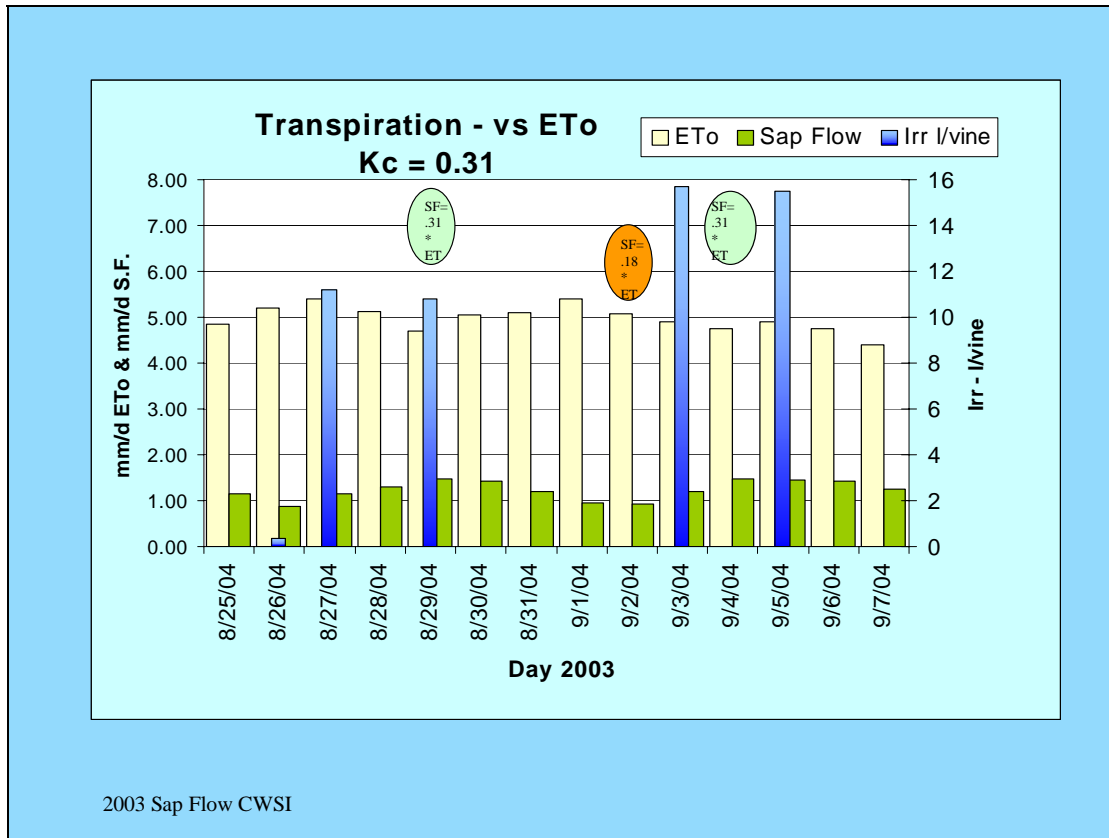


This chart shows an alternative comparison of sap flow vs. ET. The ETc may also be shown in ml/hr per vine by dividing $ET_o * K_c$ per hectare by the number of vines per hectare (2240/hc). Ten representative days are shown here, with sap flow in green, and ETc in orange. The flow rates are shown to decline within two to three days after irrigation. An accurate comparison can be done only with daily totals.

Then ET_o – Evapotranspiration index from a weather station is recorded simultaneously. The ET is very consistent at this time, and driven by very clear skies and very warm temperatures around midday. In this chart the ETc is converted from mm to ml/hr on a per plant basis.

The Soil moisture is recorded as a reference, and provides some feedback on the irrigation cycle and insight on the water status vs. stress. The soil in this area is sandy loam, based on a field capacity of about 20% volumetric soil water content. The sap flow rates show significant decrease, even within three days of irrigation.

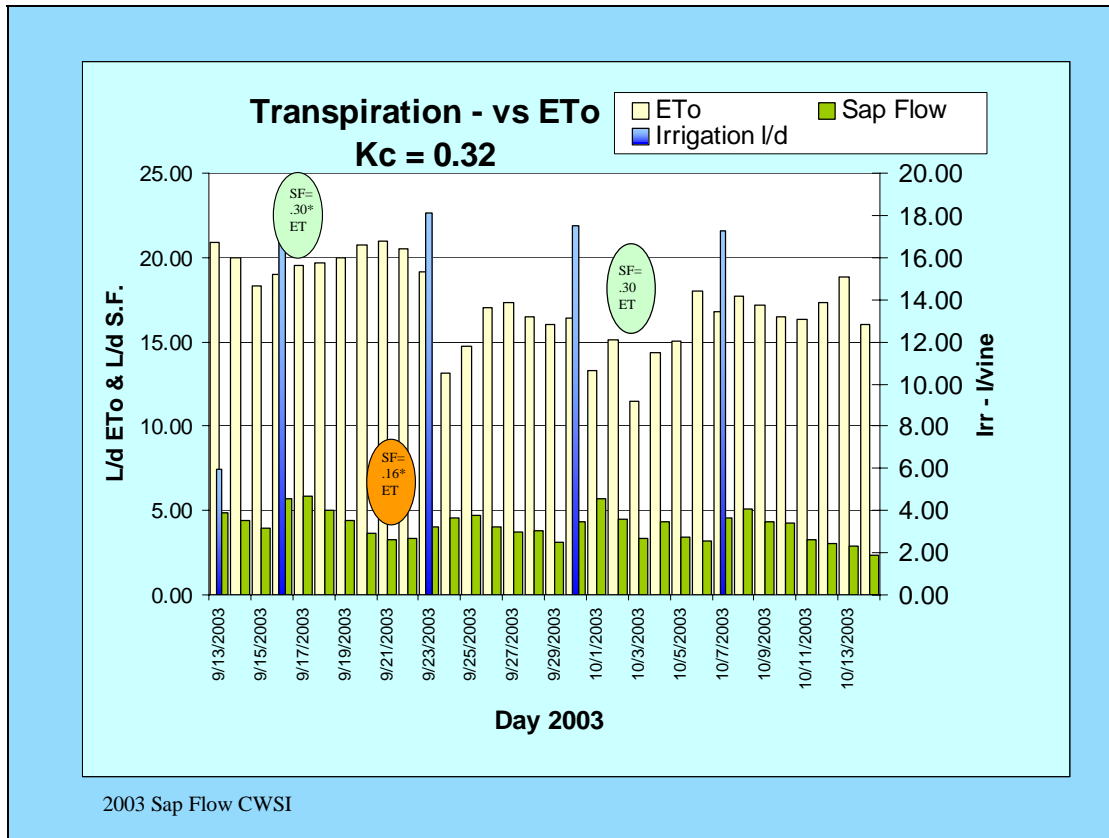
ET c is the crop ET, the ET_o reference times the Crop Coefficient (.32). The Crop coefficient is estimated by some general references at 0.5, however the well-watered crop coefficient measured was actually .32 as explained later.



In this chart all the hourly data is converted to sap flow on a daily basis. All the sap flow for 24 hours is added together and multiplied by the number of plants per hectare, then converted to mm depth of water consumption. Irrigation is shown on the right scale in liters per plant. ET is shown as the reference ET provided by the CIMMIS weather station. ET is provided in mm/hr, so it is also added together for 24 hours to provide the daily ETo.

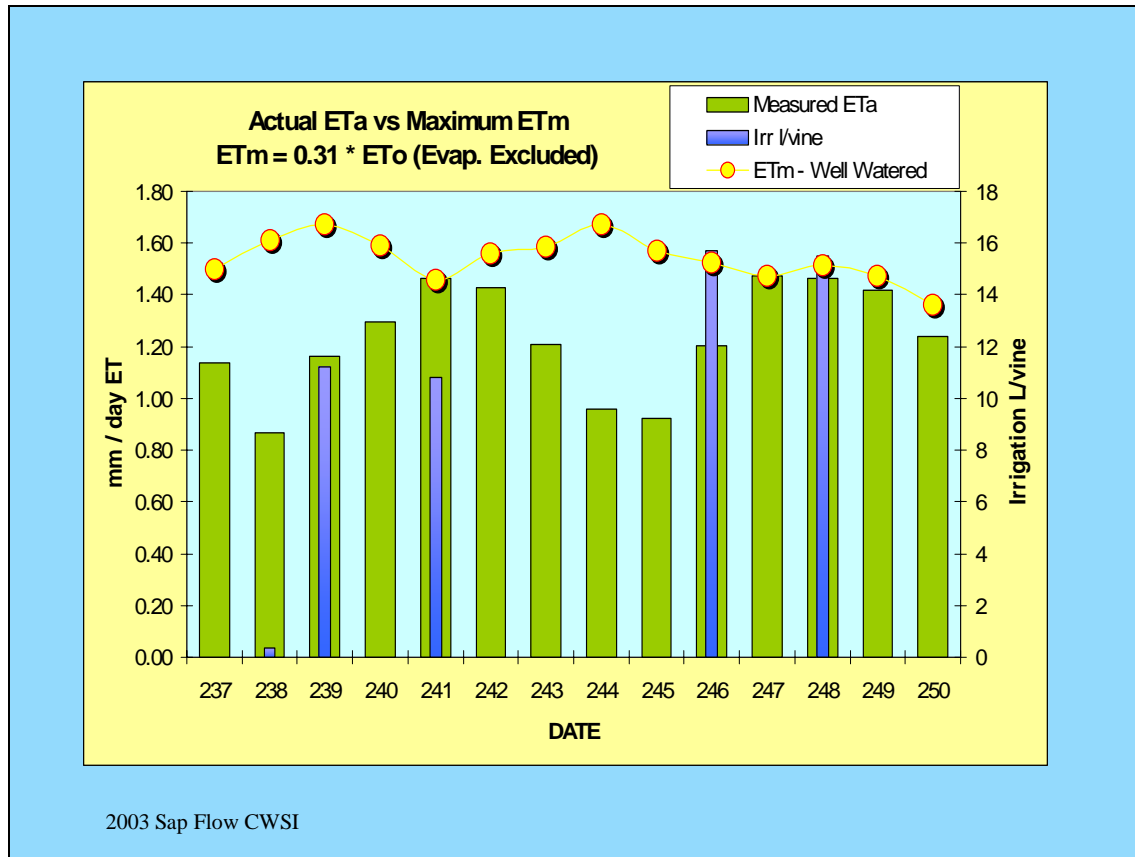
During well-watered conditions, transpiration (actual ETa) correlated to ETo at a constant ratio throughout the measurement period. On 8/29 and 9/04 the transpiration was at its maximum relative to ET. On both 8/29 and 9/4 the ETa/ETo was 0.31. Thus the well-watered crop coefficient is 0.31. For simplicity, and consistency we did not estimate an evaporation component to add on to the transpiration by sap flow.

Sap flow declined to 18% of ET as recorded on 9/2. Clearly the vines are very responsive to the decline in water availability, and significant water stress is measured four days after irrigation. In August 2003, the vineyard manager scheduled two irrigations per week, and to avoid significant stress, increased the volume from 10 L/vine to 15 L/ vine.



This chart shows the data for an entire month. The data is presented in liters per vine sap flow and liters per vine ETo. The results are similar to the previous chart in mm water use. The analysis process is identical either way.

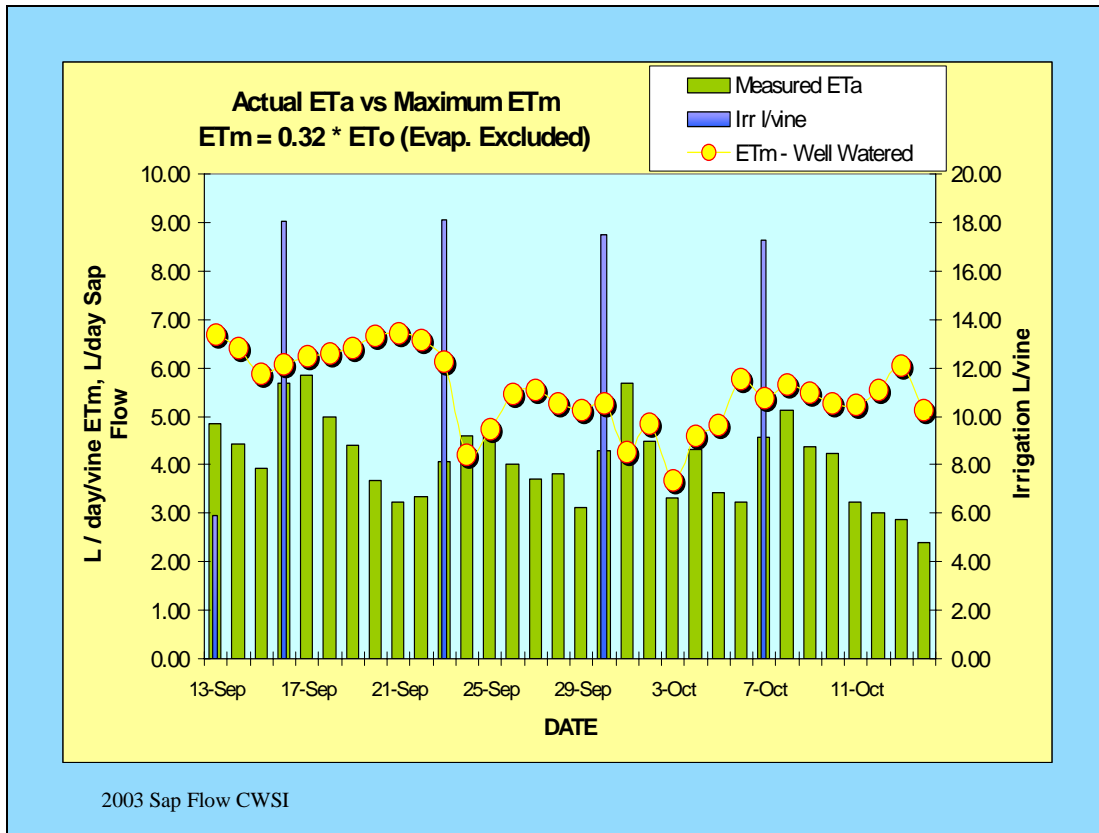
After the four irrigations in this period, the maximum transpiration for two days after each irrigation was averaged together. The average for all eight days was $0.32 * ETo$. Therefore the average crop coefficient for the well-watered days was 0.32. There appears to be no significant difference in Kc from late August through the middle of October.



Back to the September data, we can now chart the ETm from $Kc * ETo$. The yellow circles (sun symbol) show the projected transpiration when well watered, and the actual transpiration is the green bar. The difference is the transpiration decline caused by water stress.

Note that as the sun symbol goes higher (days 243-244), stress comes on quicker and greater than when the sun is declining (days 249-250). No-stress days are the ones when the sun and the green bar are equal or close to the same value (days 241, 247, 248, 249), since ET and ETm are on the same scale in mm/day.

Slide 12

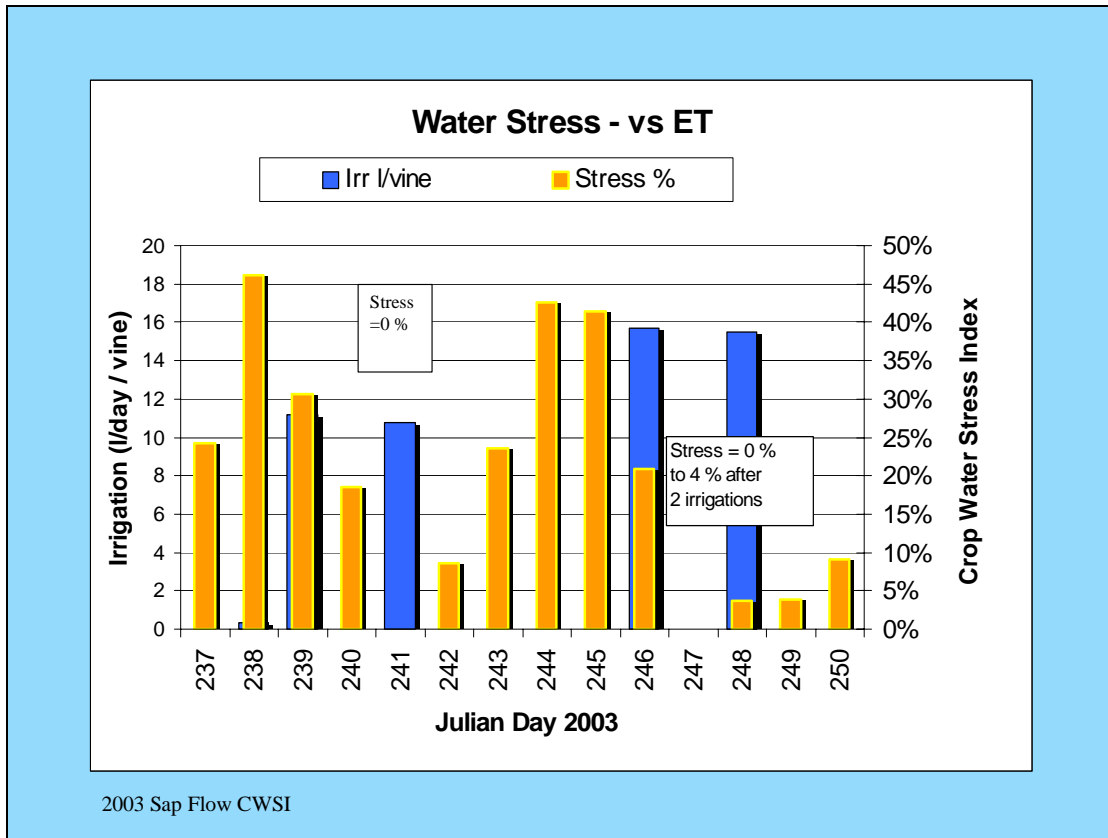


This is the September - October data analysis similar to the last chart, only in liters/day. $Kc * ETo$ is charted as ETm . Irrigation was scheduled consistently every seven days, showing the transpiration stress very easily.

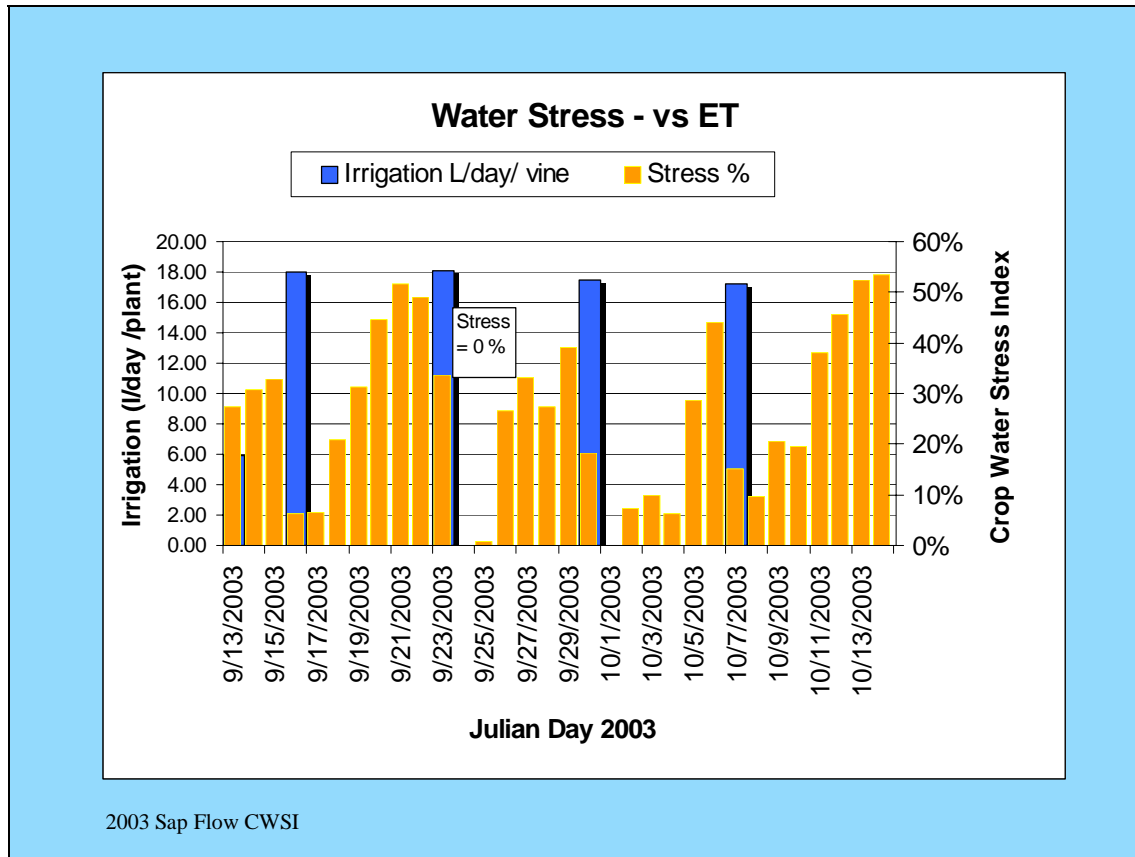
Again, on cooler days such as 24 - 25th Sept, there is negative, or no stress, but still water use is fairly high due to a recent irrigation. After subsequent hotter days, 26 to 29th Sept., stress is evident again.

Another important observation is the 24 hours of recovery time noted after irrigation, when transpiration has declined significantly for five days in a row (Sept 22). A full day after the irrigation the stress was reduced to zero. The same recovery time is shown on Sept 30. This is not the case when there were two irrigation cycles in the same week. In the previous slide, there was a recovery delay of one day after the first irrigation in a week, and no stress or recovery delay on the subsequent irrigation two days later. When there were two irrigations per week, not only was more water applied, but there were two more days when there was no stress possible.

The next and final step is to quantify the CWSI for individual days. Overall it is possible to compute the CWSI for the daily data shown here or for a long term average CWSI. In the example above the ETa , actual transpiration, was 131 liters per plant, and ETm added up to 177 liters per plant. Thus the overall CWSI is 0.26, or 26 % stressed.



The final step in CWSI analysis is made here. The transpiration stress index was calculated daily and increased as water depleted from the soil. Note the delay in stress reduction is one to two days after the first irrigation in the week. A direct correlation of decreased water potential and volumetric water content to increased transpiration stress is shown by the experiment (data not shown here). In this period from mid Aug. the average stress of all the daily numbers was 20%. This CWSI average is the same as the total derived from the transpiration (17.25 mm) and the ET_m projected (21.57 mm) for the two-week period.



The final analysis of CWSI for 32 days. The average of the daily stress is 25% for the 32 days. This is only slightly different that the stress derived from the total transpiration for the vines (130.9 l) vs. the total ETm (177.3) for the same 32 days. The average stress was 5% more for irrigation once a week, (about 18 l / plant each week), compared to the stress from irrigation twice a week (about 26 l /plant each week).

Summary	Aug - Sept	Sept-Oct.	
No Days	14	32	
ET CIMMIS	69.6	124.2	ETo mm
Actual Water Use	17.3	29.4	ETa mm
Water Applied	53.6	76.9	l/vine
Water Applied mm	12.0	17.2	mm
Irrigation Surplus/Deficit	-30%	-41%	Deficit
Well Watered Crop	21.57	39.8	mm @Kc=.32
Transp Stress - CWSI.	20%	25%	

Conclusions:

- Water stress index can be calculated real time with daily tracking of sap flow and ET under field conditions.
- The Sap Flow CWSI method is unique in showing reaction to weather and water application with collection of the required parameters.
- ETm and the correlated Crop Coefficient, Kc can be derived at any time with sap flow data, however the irrigation status and water status must be observed.

2003 Sap Flow CWSI

Conclusions:

- **Flow4 Sap Flow is sufficiently accurate and responsive to correlate sap flow with ET provided that four sensors are weighted and averaged to the crop. Sensors were properly installed and maintained. ET from a nearby weather station is required.**
- **Irrigation deficit and the Transpiration stress are controllable and appear correlated. More data over complete season is needed for a variety of conditions.**
- **Soil moisture provides a valuable check point for irrigation status. More observations would be required to correlate stress vs soil moisture.**
- **Crop yield and quality compared to CWSI was not known and would require more study. Plant or leaf water status was not available to correlate to sap flow CWSI and should provide additional analytical comparison.**

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2003 Sap Flow CWSI

To obtain more information or quotes for the equipment used in this study:
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