Irrigation water stress management study of vineyard transpiration with a sap flow meter

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ABSTRACT

Water balance models on non-irrigated vineyards are commonplace. Those models rely upon a correct estimate of plant transpiration rate. However, the transfer of existing models to irrigated vineyards under high evaporative demand is difficult. Irrigation practices during high vapor pressure deficit (VPD) have contrary and complex effects on vine transpiration. Monitoring vine sap-flow allows a direct assessment of vine transpiration rate and offers improved understanding of the effects that soil moisture gradients and VPD have on the plant's water deficit. Current vine-water status assessments are based on discontinuous, difficult, and time-consuming leaf-water potential measurements. Sap-flow measurements available now provide the vineyard manager with a continuous estimate of vine transpiration throughout the season. Assessing sap flow variations can indicate plant water status and provide a tool to optimize irrigation. We compare vine transpiration with stem water potential and soil moisture while explaining the advantages and inconveniences of this new method.

INTRODUCTION

Initial 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 micro irrigation 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.)

In 2002 the closed loop method was implemented by Dynamax Inc with the announcement of the FLOW4-IS Irrigation Scheduling system (US Pat No.).

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 (Kc) 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 purpose of this study was to show the relationship between sap flow stress management and the more traditional water status derived from stem water potential measurements.

By comparing the effective transpiration by direct measurement with stem water potential, we show the utility of water stress measurement by packaged sap flow systems. A positive and strong correlation of the two methods will allow us to implement an effective vine stress water management method with an automated sap flow system, and thereby save labor, cost, and time required for more traditional alternatives.

MATERIAL AND METHODS:

Experimental sites and management practices: The study was conducted in 2006 in one California vineyard (Napa Valley, CA, USA). A follow up study was performed in 2007 in five vineyards in Napa Valley. Vineyard elevation is 80 m above sea level. Rows are oriented parallel to a downgrading slope oriented towards the Northeast. Vines (*Vitis vinifera* cv. Cabernet-Sauvignon) were planted in 1989, grafted over the rootstock 101-14 Mgt, in North East-South West rows, 1.8 m apart with a 1.5 meter within row spacing. Canopy hedging after growth stopped was performed on July 19th. Cluster thinning was performed on July 27th. Water volume per irrigation ranged from 0.9 to 8.8 mm per vine across the vineyard. There were 24 water applications events until harvest. Our plot consisted of 18 vines planted next to each other over 3 adjacent rows.

Soil Water Status: we determined available soil moisture for the plant along the soil profile explored by the sensors. We weighed the soil moisture measurements (volumetric content) by the thickness of each soil horizon where a sensor had been installed.

$$SM(t) = \sum_{i=1}^{i=5} f_i \bullet SM_i(t) \qquad \text{(Equation 1)}$$

where f_i is thickness of soil layer *i*, and $SM_i(t)$ is daily average soil moisture reading at soil layer *i.*

Plant Water Status: Stem Water Potential (SWP) was measured with a pressure chamber (model 600, PMS Instrument Co, OR. USA)., SWP was measured 30 times between May 15th and October 11th. Leaves were bagged with a plastic sheet and an aluminum foil at least 40 minutes before measurements following the methodology of Chone (2001). SWP was measured at solar noon on 3 leaves per vine and each leaf was located at the bottom part of the canopy (lower third), on the shaded side of the vine. Pre dawn leaf water potential were measured throughout the season on the same vine, just before the sunrise.

Sap Flow Transpiration Measurements
Sap flow was measured on two vines using the FLOW-4 DL logger (Dynamax, Inc., Houston, TX, USA). Sap flow measurements were scaled at the plant level according to the leaf area estimates on a per plant basis. The ratio of leaf area for measured vines over the total leaf area for the test area provided the conversion of sap flow to actual evapotranspiration (ETa) in mm.

Sap Flow Gages produced by Dynamax provided measurement of transpiration in selected vine cordons, avoiding irregular basal trunks or ground temperature gradient effects. The basis of the sap flow sensor is the energy balance method derived from a constant heat source applied to the plant stem (SHB method). The sensors are precision instruments that measure power transfer from a heater strip to the stem, the ambient and into the sap flow. Sap cools off the heater in varying amounts corresponding to the flow rate. The sap flow (F) was computed and saved in grams per hour and accumulated grams per day by a formula using the heat applied to the stem (Pin), the radial energy from the stem (Qr), the vertical conducted heat loss (Qv) and temperature differences (dT) of sap above and below the strip heater. The Flow4 system provided for this experiment recorded the signals and calculated the sap flow (F) with a well accepted energy balance formula (Van Bavel 1987):

$$F = (Pin - Qv - Qr) / Cp * dT \ (g/s) \qquad \text{(equation 2)}$$

Various expert methods to filter out nighttime, weak or erroneous signals were applied so that calculated data values were consistent with generally accepted sap flow methods (Lascano, R.J., Baumhhardt, R.L., Lipe, W.N., 1992).

Meteorology and Phenology : A meteorological station provided data, less than 20 m from the experimental vines (Adcon weather station, Adcon International Inc., CA, USA). Air temperature, relative humidity (RH), photosynthetic active radiation (PAR) and wind speed measurements were recorded every 60 seconds and averaged every 15 minutes by a data logger. No precipitation was recorded between June 16th and October 2nd. During that period, daily temperatures showed an average value of 20 ^{0}C ranging between 13.9 ^{0}C and 26.8 ^{0}C for minimum and maximum respectively. The daily vapor pressure deficit was on average 1.18 kPa. Peak values for vapor pressure deficit reached 6.6 kPa and were recorded on July 17th and August 6th. Main phenological phases were recorded at all sites.

Leaf area index and fruit weight estimates: We estimated LAI in August when all the leaves were still green by using a direct method of measurement. First, to determine the leaf area per vine, we sampled 3 vines at each plot. We counted the number of shoots per vine and the total number of leaves per shoot on 6 shoots per vine. We randomly sampled 6 leaves per shoot along 6 shoots per vine. Leaf area was determined using a leaf area meter (model LI-3100, Lincoln, Nebraska USA). Leaf area index was calculated as follows:

$$LAI = Nsh \bullet Nlv \bullet LA \bullet d \qquad \text{(Equation 3)}$$

Where Nsh = number of shoots per vine; Nlv = average number of leaves per vine; LA = average leaf area/leaf; d =number of vines/m^2. Fruit weight per vine was estimated on harvest day for each plot. In both vineyards clusters were harvested and weighed from a number of vines per plots. Fruit weight was divided by the number of vines to get an estimate of the fruit weight per vine in each plot.

Soil and root: soil samples were extracted with an auger, 10 cm away from the vine row. We measured bulk density ($g.cm^{-3}$) and soil texture (% of clay, loam and sand) at 3 different depths ranging from 0.10 to 0.75 m. Bulk densities were between 1.19 and 1.34 g cm^{-3}. Sand content was between 29% to 48%. Root density along the soil profile was estimated from a 150 cm deep backhoe pit at each site. We counted the number of roots present in 5 different soil layers (0-20 cm, 20-40 cm, 40-55 cm, 55-70 cm, 70-90 cm). Soil moisture was measured using capacitance probe (C-Probe™ Agrilink Int. Inc., CA, USA). Soil moisture probes were placed under the vine row, 30 cm away from the trunk, at depths of 10 cm, 30 cm, 50 cm, 60 cm and 80 cm below ground. The data logger recorded one measurement every 5 minutes. We averaged to determine daily soil moisture content over the first 90 cm.

Additional data was taken in 2007 from three vineyards with the same variety, Cabernet Sauvignon, and included the same information as previously cited in 2006.

RESULTS

The problem with scheduling irrigation by only soil moisture or only by a water balance is the fine detail, and narrow moisture ranges needed to determine a site specifiic irrigation strategy. Furthermore the actual transpiration deficit varies widely due tho the plant response over a very narrow range of soil moisture found in realistic field conditions. The soil characteristics will also vary widely from one irrigation block to another, and the results may not be translated from one area to another. In Figure 1 the transpiration for a typical plant is shown varying over the season as the soil moisture changes. The soil water content through the root depth was measured as an average over 900 mm. Soil water content varied from .13 to .17 m3.m-3, yet the transpiration shows a variability of 175 to 400 g.d-1. End of the season tanspiration decreases as the vine senesces after harvest, and VPD and Eto decline. Eto for the season is shown in Figure 2. We found that Eto peaks at 5 mm . d –1 declined to 2 mm . d –1 as the season ended. Early and laste season stress and transpiration would not neccesarily correlate or depend on soil mositure.

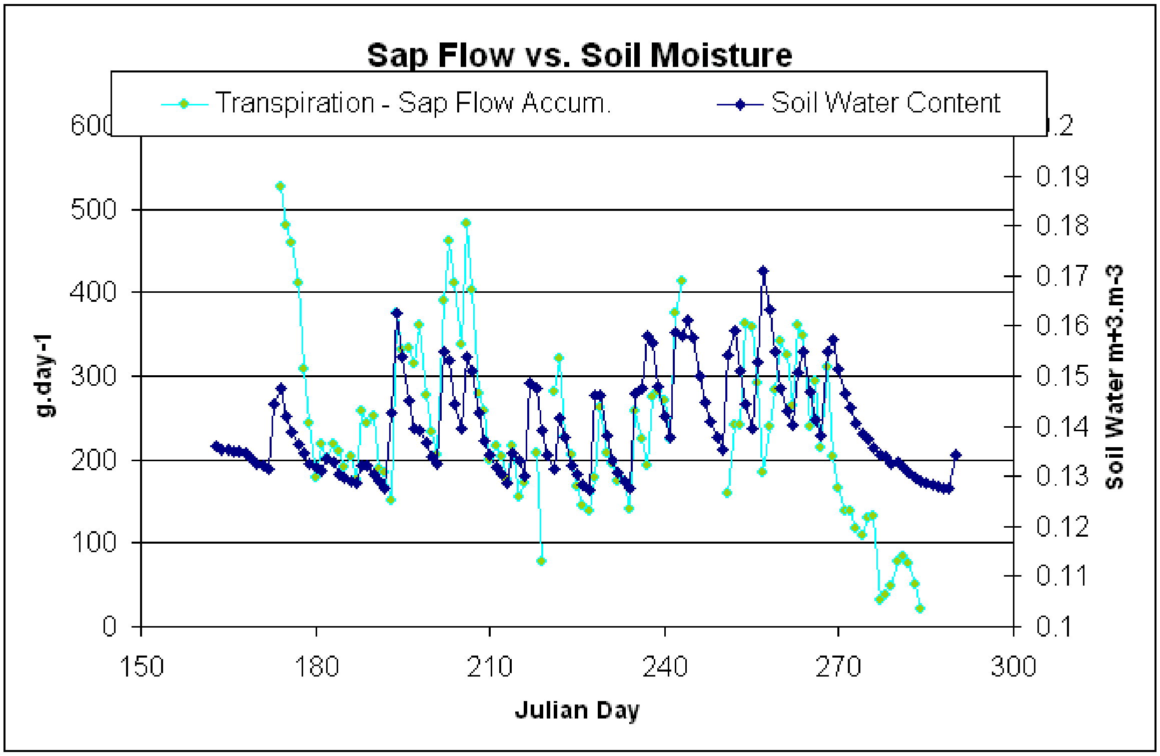

Figure 1. Relationship between Transpiration and soil moisture.

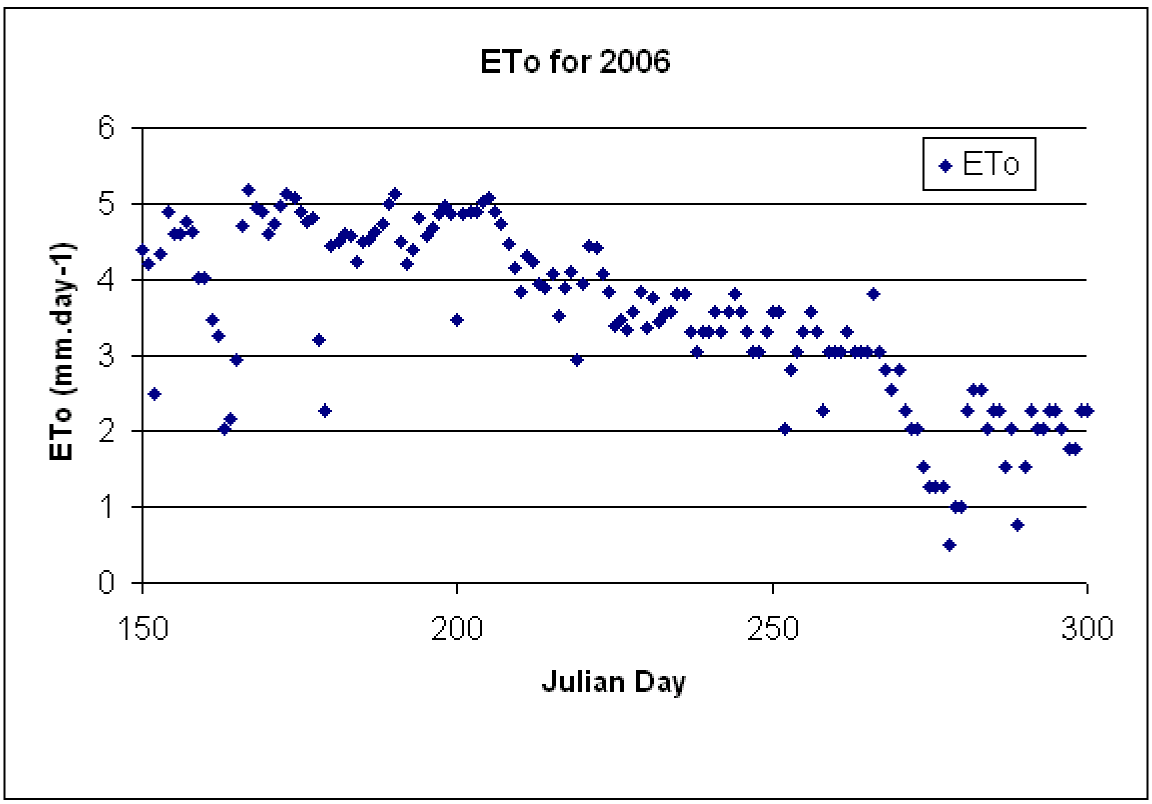

Figure 2. Eto, reference evapotranspiration during the growing season in 2006.

In Figure 3 the crop coefficient Kc is shown as the season progressed. The values represent a Kc from early season through a wide variation with respect to soil moisture. In the literature and in the FAO guidelines (Publ 56) there is no term for the real time crop coefficient, however we may borrow the term for Kc adj, the Kc determined from the ET c adj, which is defined as the evapotranspiration determined during non-standard conditions such as vines under water stress.

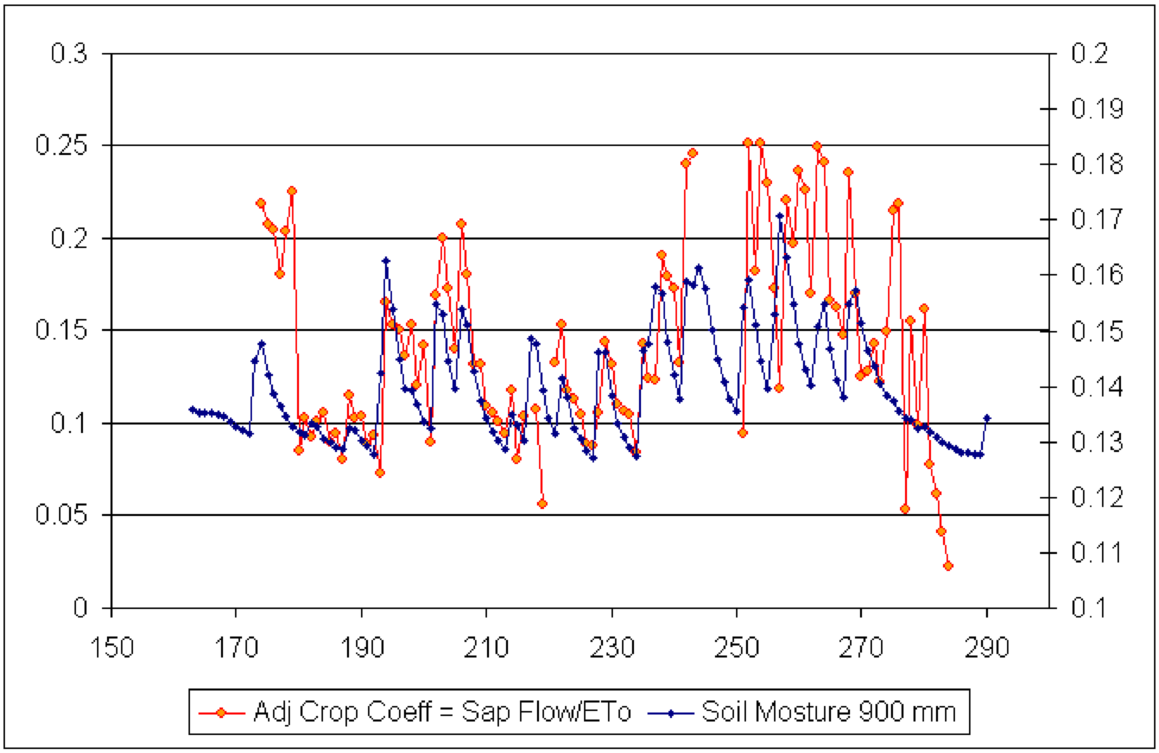

Figure 3 – Crop Coefficient Kc adj varying throughout the season, and under varying soil moisture conditions.

The irrigation events for 2006 are shown in Figure 4. The typical irrigation management method was used to induce stress, and to provide for a high quality wine grape product.

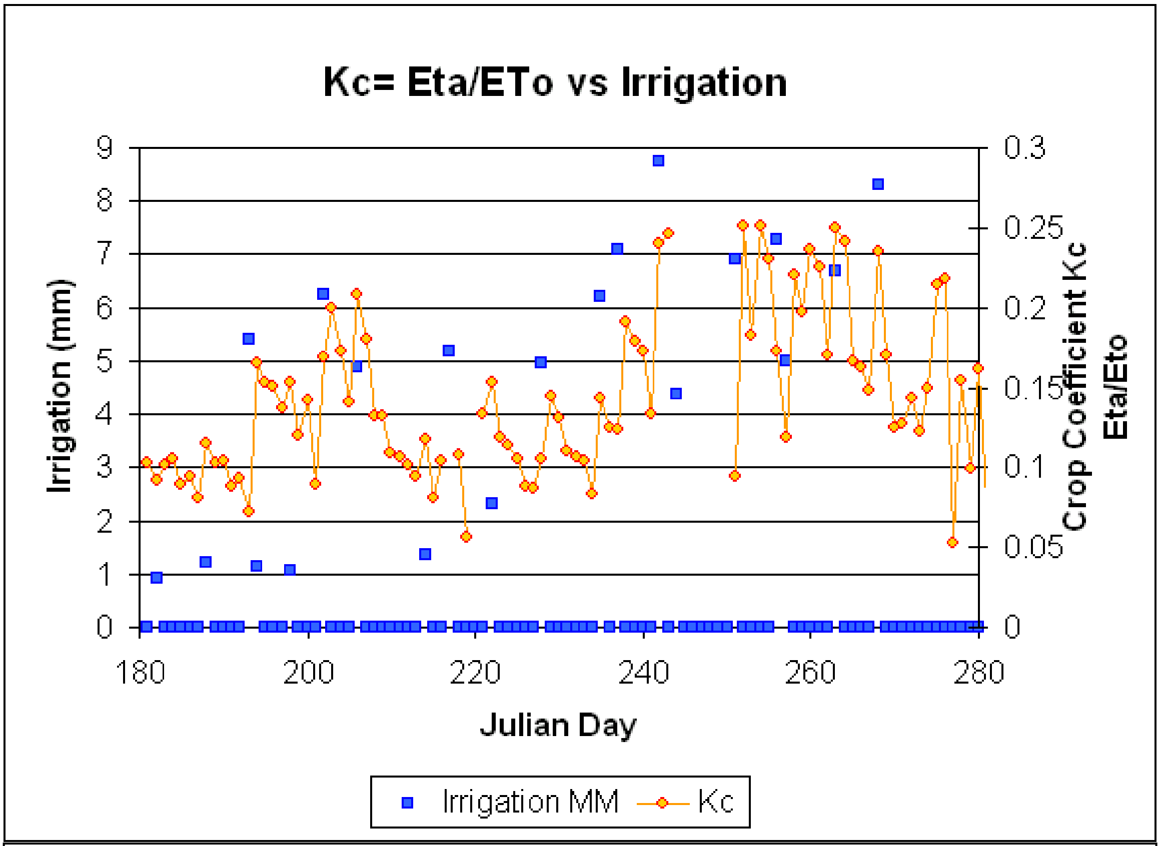

Figure 4 Relationship between Transpiration peaks and Irrigation events

Irrigation varied from 1 to 9 mm over the season to maintain a reletively high stress level, and no less than a -15 bar stem water potential. Note that the effects of water stress decreased rapidly after the large irrigation events, and daily transpiration increased Kc over 1.7 rapidly after almost all irrigations exceeding 5 mm in one day.

The 2006 stem water potential reeadings were made mid-day periodically, and irrigation adjusted, possibly scheduled on the same day, or on the following evening. As a result there was limited stem water potential data during well watered conditions. Figure 5 does show that there is a positive correlation to the SWP and the Kc adj. The Kc in this case was determined with transpiration readings from only two sensors, and adjusted by leaf area estimates. Thus we expected that with more sap flow sensors per plot, and more SWP readings before and after irrigation, a much clearer relationship will be determined and with improved correlation.

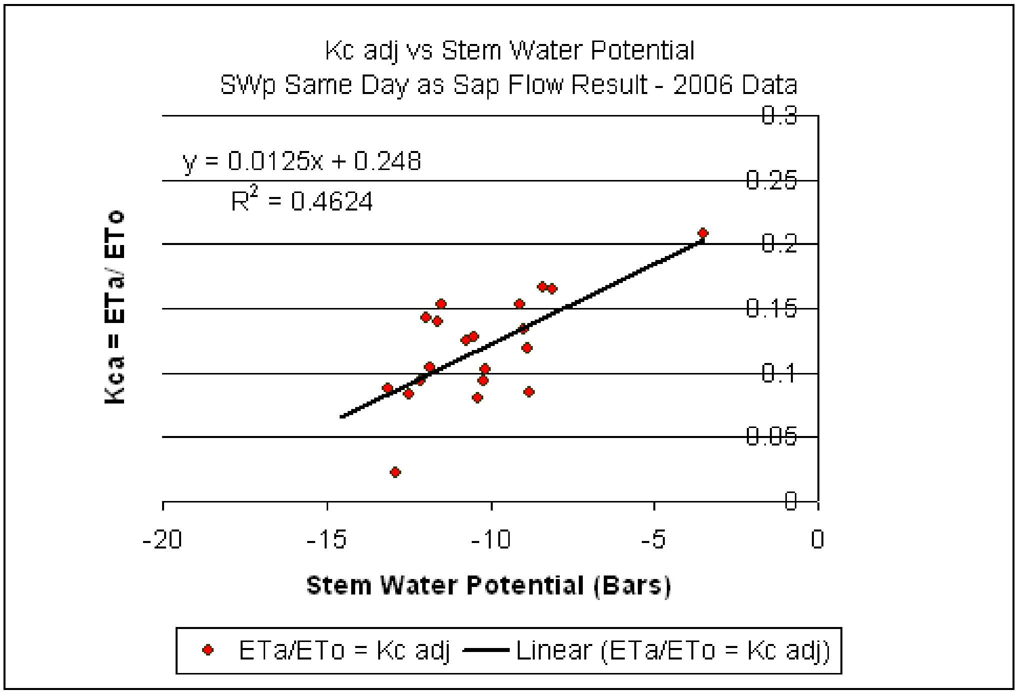

Figure 5 - Relationship between Kc adj and Stem water Potential

In 2007 we made an adjustment to the procedure by reading SWP much more frequently to determine a fixed relationsship between sap flow derived Ks, the stress coefficient and the stem water potential. In figure 6 there is consistent data showing that relationship between stem water potential and the varying crop stress factor Kc. The crop stress factor is provided in the FAO guidlines publication 56. (FAO Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56). After setting the leaf area parameters, the Flow 4 sap flow system automatically indexed sap flow to the irrigation block area. The ratio of the indexed sap flow on well watered days provided the Kc max, maximum ET over ETo. By calculating the reference ETo multiplied by the Kc max, we determined a maximum Etm for all days.

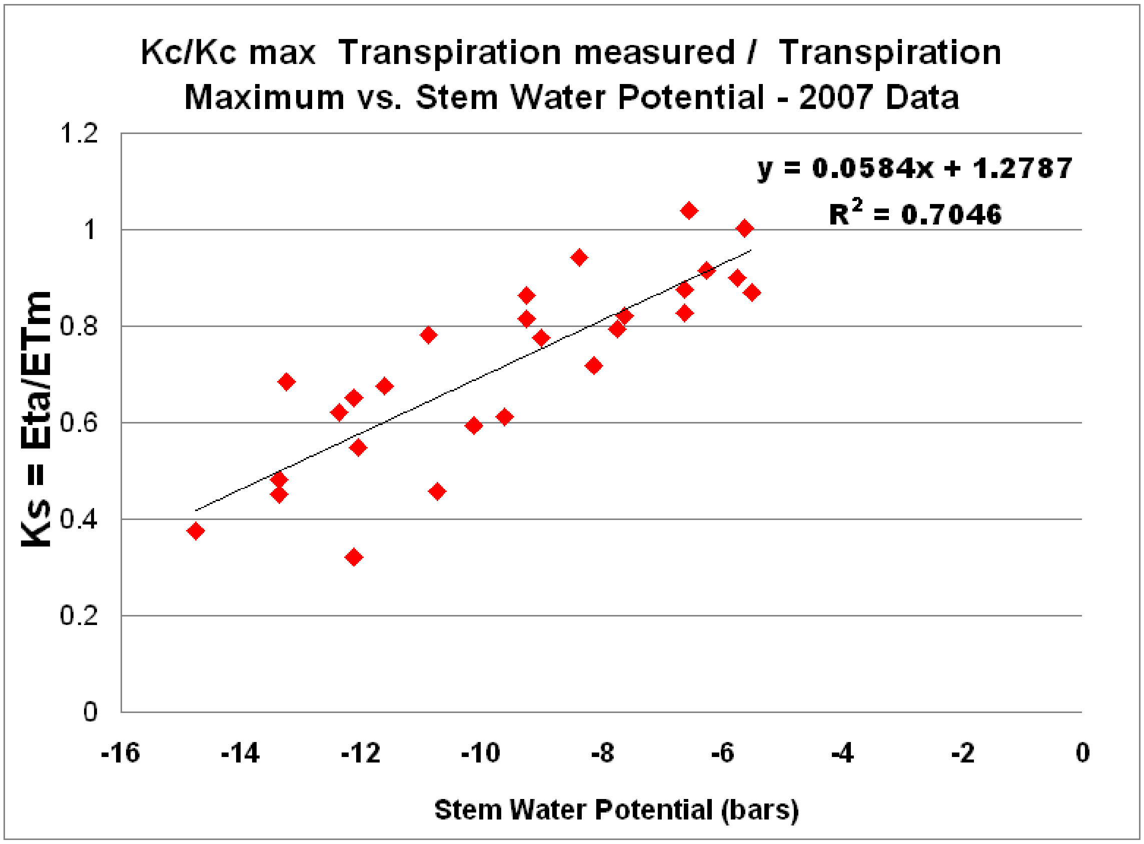

Figure 6 – Ks stress coefficient, with respect to stem water potential.

The Ks, stress coefficient with the sap flow method, is simply

ETa / ETm = Kc adj/ Kc max

on the day of concern, where Kc Max is determined under the well watered conditions (however see discussion on conditions). In 2007 we included a data set from three vineyards, on the same variety but with a great variation in spacing and plant leaf density, and thus the results are representative of several vineyards pooled together. By indexing the Ks with individually determined Kc adj, and Kc max, all the results are normalized in Fig 6. Each of the days with a SWP measurement, and a confirmed sap flow result are displayed in Figure 6.

Conclusions

Though the application of sap flow information we have concluded there is a direct relationship between the actual stress coefficient, Ks, and the stem water potential. By observing ETo, soil moisture, irrigation and resulting water balance before and after irrigation, we noted the trends that caused transpiration deficit. However the integration of all the factors appear in the final correlation of SWP to the transpiration devrived from crop stress. In Figure 6, the stress index was 1 (no stress) at a SWP of about 5 Bars. Since a deficit irrigation is in effect, the ususal crop coefficients commonly used by agricultural commmodities growers and irrigators are not confirmed here. Stress index at a SWP of -12 to –14 Bars indicate a transpiration drop of 50 % (Ks=.50) below the normal (deficit) irrigated transpiration.

The relationships showing a real time, daily, Kc adj, can be determined for a specific vinyard and variety. In fact this is needed if one intends to compare the Kc from one block to another. In the limited data set from 2006, there is a indication of the Ks (and Kc) to the SWP, however we conclude that at a minimum four sap flow sensor readings should represent a Eta measurement, and we conclude that at least SWP readings relationships should be observed from one to two days after an irrigation.

The next steps are to provide Kc relations and Ks factors to growers with a wider variety of wine grape vines, and under specif field arrangements. This study shows that is is possible to increase future improvements in projecting plant transpiration stress, and a yield and quality improvement production methodology based on sap flow stress measurment methods.

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Definitions:

(FAO Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56)

ET	evapotranspiration [mm day^{-1}]
ET_o	reference crop evapotranspiration [mm day^{-1}]
ET_c	crop evapotranspiration under standard conditions [mm day^{-1}]
$ET_{c\ adj}$	crop evapotranspiration under non-standard conditions [mm day^{-1}]
$K_{c\ ini}$	crop coefficient during the initial growth stage [-]
$K_{c\ mid}$	crop coefficient during the mid-season growth stage [-]
$K_{c\ end}$	crop coefficient at end of the late season growth stage [-]
$K_{c\ max}$	maximum value of crop coefficient (following rain or irrigation) [-]
K_s	water stress coefficient [-]
$ET_{c\ adj} = K_s\ K_c\ ET_o$	Formula defining Ks relative to ET adjusted for stressed conditions, ETC adj