Improving winegrowing with sap flow driven irrigation – a 10-year review

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Abstract

The Fullerton Sap flow meeting presented lots of scientific evidence showing how useful sap flow measurements could be for application in horticulture. For the past 10 years, our company, Fruition Sciences has been using real time sap flow data to improve irrigation scheduling across many vineyard regions worldwide. However, despite its solid scientific basis, converting a theoretical concept into a fully actionable decision tool has been a challenge. The goal of this article is to examine how and why viticulture has adopted sap flow monitoring to improve irrigation strategy for commercial applications. By dissecting historical steps leading to the successful implementation of sap flow in viticulture; it is illustrated how it is possible to overcome the challenge of introducing a new technology in a traditional industry. In the context of precision farming, adopting sap flow metrics means disrupting traditional habits and pre-existing status quo on irrigation and vineyard management. It is discussed how understanding the wine market guided strategic decisions in order to convert a scientific concept into a business opportunity. Through a few case studies it is described how sap flow monitoring has gained popularity in the wine industry and why it contributes to improving vineyard management beyond irrigation strategies.

Key word: sap flow, viticulture, irrigation, berry ripening, nitrogen deficit

INTRODUCTION

A lot of results have been published on sap flow measurements performed over many different crops. Numerous studies have validated the use of sap flow measurement to improve vine water use monitoring. In this context, I would like to discuss what specific challenges had to be overcome to disseminate the use of sap flow in the wine industry. Because adopting sap flow metrics disrupts traditional irrigation practices, it requires an additional effort from vineyard managers and winemakers. As such, as it is typically the case when introducing an innovation, a selected group of early innovators was targeted at first.

Unless a new legal framework challenges traditional habits, adopting changes in vineyard management practices is a slow process. For instance, since irrigation has become legal in 2006 in southern France, many vineyards have invested in irrigation technologies. A drastic change has been adopted, even if there was no previous experience on how irrigation could modulate vineyard historical performances. Thus, when legal incentives exist, new technologies can be rapidly adopted while their effect in the short or in the long term may be unknown.

By contrast, there is no legal incentive to promote the adoption of sap flow technology. In this context, a creative strategy had to be developed to promote the use of sap flow monitoring. What were those steps? How and why was it possible to disseminate the adoption of sap flow in the wine industry?

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Why wine makers are interested in sap flow technology

1. Wine scores and vintage effect.

Some features intrinsic to the wine industry provide winegrowers with specific incentives to adopt sap flow technology. First, among wine consumers and winemakers a historical conception that seasonal vine water status variations relate to wine sensorial properties and thus wine pricing already exists. The effect of one-season climatic conditions on wine composition is called the "vintage effect" by winemakers. For instance, drier winegrowing conditions in Bordeaux have typically been correlated with higher wine prices. Thus, under oceanic climate, dry seasons are often expected to have a positive "dry vintage" effect on wine. Second, numerous studies have reported how vine water deficit variations can affect positively fruit and wine compositions under different climates. Third, following each harvest, wine critics appreciate the "vintage effect" by attributing wine scores. Season effect on vine performance, and particularly vine water use, is expected to influence wine sensorial properties and wine scores.

For those reasons, winemakers are naturally interested by innovative methods revealing the footprint of a season on vine water use variations. The wine consumers and critics are also receptive to sap flow as a way to reflect the vintage effect.

2. Highlighting vineyard originality.

Wine pricing is very dependent upon the originality of the production site. Wine composition, such as concentrations in anthocyanin or tannins is directly affected by fruit composition, which in turn is affected by viticulture practices. Many scientific articles describe how different irrigation regimes modulate fruit anthocyanin accumulation or wine coloration density. Thus, knowing how to optimize seasonal vine water use profile through a precise monitoring technique can be a strategic advantage for the winemaker since it directly effects wine composition. Winegrower can also use sap flow variations over a season to reveal a unique "plant signature" attached to a unique place. The time profile of vine water use can be interpreted as a site-specific trait highlighting an original vineyard context and framing fruit ripening conditions. By recording continuous vine water use variations, winemakers can also track the effects of contrasted farming strategies on vine performance. After harvest, winemaker can "taste" the effects of contrasted vine water deficit profiles on wine composition.

Analysis of vine sap flow variations provides an opportunity to create a link between wine consumers and site-specific conditions leading to wine production. This information is useful to distinguish why a wine is different from others in a competitive market. An iconic winemaker, a unique vineyard topographical feature or an original history can imprint an "inimitable" character to a wine bottle. Similarly, sap flow contributes to highlight what makes a wine unique based on the vineyard it is sourced from.

3. A global and competitive industry.

On a global scale, an increasing number of wine growing regions are developing under semiarid and warmer conditions. The emergence of new winegrowing regions (like China) increases global competition. With increased pressure on vineyard growing conditions, due to water scarcity, warmer temperatures and increased wine market competition, a greater need to optimize viticulture practices arise.

As new vineyards are being developed and managed under higher temperatures, optimizing vine water use variations is becoming a strategic practice to maintain vineyard financial sustainability. For instance, warmer and drier winegrowing conditions directly impact winemaker decisions: timing of harvest can become earlier in response to greater water deficit; when dehydrated fruit is harvested, cellar operations must adjust for higher sugar concentration leading to higher wine alcohol content.

In conclusion: winemakers are naturally sensitive to the benefits attached to sap flow monitoring. It is an opportunity to improve fruit and wine composition via improved vine water status management. Sap flow profiles highlight site and vintage specific effects and provides an opportunity to adjust farming strategies in a context of climatic changes. As such, winemakers welcome sap flow technology to improve wine production. Such features, specific to the wine industry justify why amongst many other horticultural crops, grape has been prompt to revisit the status quo on irrigation practices, even without legal incentives. However, a compelling case from a winemaker standpoint is not necessarily a compelling case from a vineyard manager standpoint.

How did vineyard managers become interested in sap flow technology?

In viticulture, the production cycle is slow. It takes 2 to 3 years after planting for a vineyard to produce and there is under most winegrowing climates only one fruit production per year. In this context, the reward for optimizing irrigation is fuzzy.

First, the opportunity to improve irrigation practices only applies during a fraction of the year.

Second, imposing a moderate level of vine water use at key stages of the season is not the only factor likely to improve vineyard performances. However, the risk for not applying enough water is an immediate penalty for the vineyard manager: fruits dehydrate; yield and money can be lost.

Third, as a vineyard is a perennial structure, performance improvement resulting from changing an irrigation strategy may need multiple seasons before fruit quantity and quality are positively impacted. Authors have reported that amount of fruit produced one year is determined by water stress from the previous year (Guilpart et al., 2014). Long term studies of different irrigation strategies and their consequences on perennial structures such as trunk diameter or root mass distribution with soil depth have shown that vineyard performances are impacted by the effect of one season to the next. (Edwards and Clingeleffer, 2013). In practice, vineyards historically irrigated weekly or biweekly, are often showing a root profile preferentially developed in topsoil horizons. Root tips are typically more concentrated within the soil section underneath the dripper. By gradually applying water less frequently, the root structure will eventually be modified, however this may take more than one season. Thus, due to its perennial nature and the carry over effect of past seasons on yield and on vineyard root structure, production improvement in response to sap flow driven irrigation may be slow to observe and span over several years. From that point of view, adopting sap flow technology may look like a slow return on investment.

Fourth, challenging the status quo on irrigation will impose deep modifications in logistics and overall vineyard management. For instance, sap flow driven irrigation usually leads to the application of larger volumes of water less frequently. This shift in water allocation programs across multiple vineyards will modify water pumping regimes, water distribution scheduling and vineyard workers task hours. Sap flow driven irrigation will also challenge vineyard managers' own expertise particularly when irrigation is traditionally decided based on visual observations. It may be disconcerting at first to accept that vine visual symptoms can be misleading. When higher sap flow rates are measured under drier atmospheric conditions (i.e., high vapor pressure deficit) it indicates no soil moisture restriction even if leaves are folding away from the sun. Consequently, triggering irrigation based on leaf visual cues under dry air conditions is not justified when sap flow rate is simultaneously high.

Those observations highlight why vineyard managers can be more sensitive to the risk and complications associated with irrigation changes in response to sap flow monitoring than its rewards on fruit and wine composition. In this context, 10 years ago, the adoption of sap flow driven irrigation met a lot of resistance in viticulture, despite its sound scientific basis. Consequently, sap flow monitoring was implemented at first by early adopters in situations where winemakers had a strong influence on vineyard decisions.

From a scientific concept to a business opportunity

1. Building a scientific case for a sap flow approach in vineyards

To convince early adopters to implement a sap flow driven irrigation strategy, a series of trials were deployed on commercial vineyards. The goal of those trials was to demonstrate the potential for improving irrigation by evaluating different plant water status monitoring techniques, excluding sap flow at first. In 2001 by collaborating with a major California wine company in Napa two sets of preliminary experiments were performed.

One experiment took place within an irrigated vineyard located in Napa Valley in collaboration with Dr. Todd Dawson (University of California Berkeley). Within the same vineyard at 3 distinct locations through the vineyard, water samples were collected from 3 sources (9 samples total): a) from the dripper during an irrigation event, b) from the soil, obtained at various depths along the root zone but outside the wet bulb created by drip irrigation, and c) leaf petioles detached one and two days after irrigation. After analysis, isotopic composition of water absorbed by the vine and found in the petioles was not matching isotopic composition of irrigation water. However, isotopic composition of petiole water was closely matching (80%) isotopic composition of soil water coming from soil sections unaffected by irrigation water. These results indicated that irrigation water was not effective under real field conditions. Results also suggested that industry standards for irrigation best practices could be improved.

A second set of experiments was designed at two vineyards, covering 20 acres in Napa Valley. The goal was to evaluate stem water potential and leaf stomata conductance variations in response to irrigation and heat waves. For two consecutive seasons, contrasted irrigation treatments were applied within the two vineyards and vine data were collected biweekly over multiple locations. The differences between irrigation scheduling consisted of replacing either the total amount of vine water lost between two irrigation, or only a fraction thereof using an estimate of vineyard crop coefficient to compute crop evapotranspiration. Under well-watered irrigation treatment, vines were irrigated in excess of crop evapotranspiration (ET_{crop} computed using a single crop coefficient as described in Poblete-Echeverría and Ortega-Farias (2013)). Under regulated deficit irrigation treatment, the amount of water applied was computed so as to maintain vine stem water potential within prescribed limits of deficit. Simultaneous to treatments application, an analytical framework (VSIM model, Lars Pierce, CSU Monterey Bay) was used to compare measured vine water status variations with simulated output in response to climatic demand and irrigation. The modeling approach consisted of combining a canopy crop coefficient model with a soil water balance model to estimate vine transpiration, soil moisture drainage and water potential. After the first season, despite the monitoring of vine water status through modeling and stem water potential measurements, a major crop volume loss (>50%) was observed following a heat wave occurring in September, a few days before harvest and across all irrigation treatments.

After two consecutive seasons, the combination of field and simulated data highlighted two major difficulties to improve the monitoring of vine water status variations under field conditions: a) the need to improve vine basal crop coefficient estimates based on vine actual transpiration; b) the need to understand better vine transpiration response to heat wave and irrigation.

From the practical standpoint of a winegrower willing to improve irrigation strategies, those preliminary results highlighted the need to analyze in depth relationships between vine basal crop coefficient, vapor pressure deficit, soil moisture content and vine water use variations. The context was set to justify the implementation of vine sap flow to optimize irrigation.

2. Creating a proof of concept

Following preliminary results, the deployment of a large-scale project was decided. The goal was to evaluate how sap flow variations measured under real field conditions could be used as a tool to refine vineyard irrigation. Starting in 2006 and for three consecutive years, five Napa premium wineries deployed sap flow sensors in Cabernet sauvignon vineyards. The fruit harvested from the sections under monitoring was used to make wine separately. This project involved the collaboration with several partners.

Dr. Dennis Baldocchi and Dr. Laurent Misson (University of California Berkeley) provided a conceptual framework (how to relate sap flow measurements to eddy covariance and large-scale models) and measurement tools (Licor 6400). By performing additional measurements on vines equipped with sap flow sensors during specific events (before, during and after an irrigation; before and after veraison; under high and low vapor pressure deficit conditions) strategic data were acquired to refine a vine water balance model.

Dynamax Inc. graciously supplied sap flow sensors and data loggers. Dynamax sap flow sensor design consists of a heating sleeve wrapped around the vine. Heat is provided uniformly and radially across the stem section. The stem heat balance method for sap flow computation is easy to compute automatically and its principle easy to explain to first time users. The sensor does not require the intrusion of a needle into the vine. By eliminating the need for needle intrusion into the stem, winegrower concerns regarding the risk of infecting the vine and subsequently measuring sap flow from a non-representative vine was eliminated. The protocol of installation and maintenance of non-intrusive sap flow sensor is simple to implement. The sleeve is flexible and maintains a snug fit during stem diurnal contractions. This turns out to be critical, as sap flow sensors must tightly fit odd shaped stem sections. Thanks to their design, sensors can be applied over stems slightly bent or even partially necrotic as it is sometimes observed in response to pruning injuries. Because the entire stem section is heated, the heat balance method can be applied even if sap flow trajectory through the stem is tortuous. For those reasons the selection of non-intrusive sap flow sensors, instead of a needle, was key to facilitate the dissemination of sap flow driven irrigation strategies.

To further investigate the effects of environmental variations on vine sap flow, field measurement trials were completed with green house trials in the context of a PhD study (LEPSE-SUPAGRO, Montpellier, France). Lysimeter measurements were performed on potted Cabernet sauvignon vines subjected to contrasted levels of soil moisture and vapor pressure deficits. Soil moisture levels were expressed as fraction of transpirable soil water ranging from 10% to 100% as described by Lebon et al. (2003). Vapor pressure deficit levels ranged from 1 kPa to 7 kPa. Those targets imposed under controlled conditions were selected to reproduce the same environmental conditions observed naturally under field conditions in Napa, California.

3. Building a business case: "Transforming sap flow into actionable data"

By discussing the advances of the project with winemakers and vineyard managers involved in the study, the conditions under which a business model could be developed were refined. To solidify the need for sap flow technology, the practical benefits of sap flow data both for the winemaking industry and for the viticulture industry had to be highlighted. From a winemaker standpoint, measuring vine water use variations to better understand season specific effect on fruit ripening dynamics was a compelling argument. To convince vineyard managers, a list of five practical applications during the season was formulated as follows:

#1: Assess whether there is a real need for irrigation under heat wave

With sap flow monitoring, vineyard managers can revisit irrigation practices, particularly under heat waves. Sap flow monitoring will challenge water potential threshold value, as a plant-based index to assess vine water needs. During a heat wave, increased sap flow rate can be recorded while xylem water potential (midday, stem or predawn) decreases. From an irrigation standpoint, those two results seemed to contradict each other. In one hand, sap flow data suggests no need for irrigation since an increase in sap flow rate indicates no soil moisture restriction. In the other hand a decrease in water potential, can be wrongly interpreted as a need for irrigation when it is in fact caused by high vapor pressure deficit.

#2: Optimize the amount of water to apply

Vineyard managers can track the duration of sap flow increase in response to different irrigation volumes. In turn, this knowledge can be used to refine the amount of water to apply for the next irrigation. Because vineyard root structure is perennial and changes over several seasons, historical sap flow response to irrigation can be used to guide future irrigation strategies. When different irrigation volumes are applied to a same fully developed vine, it is possible to identify which water volume maximizes the duration of irrigation effect. Soil water holding capacities and root architecture impose an upper limit to the maximal amount of water that can be held as plant available after irrigation. The analysis of sap flow profile in response to contrasted water volumes indicates the upper limit above which adding more water does not prolong vine response to irrigation. Applying water above this upper limit would be a waste of water.

#3: Optimize the frequency of irrigation

By tracking simultaneously climatic demand and vine water use, vineyard managers can define and reproduce their preferred irrigation strategies across multiple seasons. A user defined vine water deficit index threshold can be used as a trigger to determine irrigation frequency objectively.

#4: Improve risk management with a continuous plant-based measurement

Unlike water potential, which as a destructive method can only provide discontinuous measurements, sap flow provides a continuous measurement in real time. This instant plant–based feedback can be used a “safety net” to make irrigation management more secure.

#5: Use an integrative measurement reflecting “terroir” effect

Regardless of vineyard specificities (vine age, scion and rootstock material, trellis system, soil properties, topography), sap flow remains fundamentally dependent on atmospheric conditions reflective of the “vintage effect”. But, beyond the effects of atmospheric conditions, sap flow dynamics also integrate complex interactions between vine, practices and soil properties. As such, the so-called “terroir” effect, which describes complex interactions between human and environmental factors impacting vine physiological response, is also characterized. Thus, outside from atmospheric conditions, sap flow also reflects the impact of present and past practices as well as vine developmental history on vine water use regulation, which is particularly relevant with a perennial crop.

By listing the benefits attached to vine sap flow analysis, it was possible to articulate why a sap flow driven irrigation strategy can provide a competitive advantage for winegrowing. At this stage, Fruition Sciences project had sparked winemakers and vineyard managers’ willingness to invest into sap flow monitoring method. However, a critical piece was missing in order to make sap flow monitoring actionable in commercial settings. The measurement had to be immediately and continuously available. A strategic expertise had to be incorporated into the project to provide sap flow monitoring in real time and create a sustainable business.

4. Building a technological framework to analyze sap flow data and user feedback

To make sap flow data available in real time, our company tested the deployment of a mesh network in the vineyard to collect sap flow data. Our company also conceived a web-application to analyze and display sap flow variations along fruit and climatic data. This framework became the central platform to discuss irrigation decisions and their consequences with winegrowers.

Prior to any sap flow sensor installation, a preliminary discussion with the winegrower must occur to select the best sampling location(s) within the vineyard. Vineyard topography, historical practices and soil variations create an important spatial variability in vineyard water status. Consequently, a sampling scheme, accounting for vineyard spatial structure has to be defined first. By combining different vineyard-mapping tools, user testimonials and a spatial model to extrapolate vine water status, the location of sap flow sampling sites within the vineyard is determined. To simplify the analysis of sap flow variations in response to environmental conditions, an index was created: the "Water Deficit Index" (WDI).

$$WDI = T / K_{cb} * ET_{ref} \quad (1)$$

T is actual vine transpiration; ET_{ref} is computed from a nearby weather station using Penman Monteith. K_{cb} is the basal crop coefficient according to the nomenclature of the dual coefficient approach (Allen et al. ,1998). The basal crop coefficient is computed as

$$K_{cb} = T_m / ET_{ref} \quad (2)$$

where T_m is maximal transpiration measured under cultural conditions. Models simulating seasonal changes in basal crop coefficient are used and adjusted according to site-specific data. Dynamics of WDI are used to interpret sap flow variations and discuss the need for irrigation accordingly.

In practice, winegrowers are told that when WDI is at 100%, vine is transpiring to its maximal level, whereas when WDI is at 0%, the vine is no longer transpiring. A few case studies are reported below to illustrate how sap flow and WDI are being used in practice.

Case studies

1. Effect of increased water volumes on vine response

Researchers have shown that changes in irrigation strategy can change root size distribution across the root profile (Edwards and Clingeleffer, 2013). Thus, changes in irrigation volumes and frequency have to be imposed gradually so that water applications match modifications in root water uptake profile. In this vineyard (Napa Valley, California, cv. Cabernet sauvignon), the goal of the winegrowing practices is to stimulate a higher root density at greater soil depths. In this context, the purpose of the treatment is to change irrigation strategy from frequent (every 3 to 7 days) to less frequent irrigations. To ensure that changes in irrigation frequency do not increase the level of water deficit between two irrigations, sap flow and water deficit index variations were monitored in real time along three seasons. Time intervals between two irrigations were increased by adding larger amount of water and tracking sap flow response. The amount of water applied was gradually increased from 5 mm for each irrigation (year 1), to 8 mm (year 2), to 8 to 12 mm (year 3). Total amount of water applied was 75 mm for year 1, 72 mm for year 2, 76 mm year 3. Sap flow data was collected over the same vines for the three seasons.

Figure 1 shows seasonal dynamics observed in WDI year 1 and year 2. We observe that WDI reaches higher values following larger irrigations applied in year 2. Using the same WDI threshold prior to each irrigation (around 40%) and applying larger amount of water with each irrigation, intervals between irrigation become larger. During year 1 irrigation is applied every 3 to 7 days and during year 2, every 10 to 15 days. Figure 1 shows that irrigation effect increases its length in time when larger water amounts are applied. Furthermore, over the period June to September, WDI seasonal average increases from year 1 (<50%) to year 2 (around 55%). We observe that applying the same amount of water less frequently reduces the severity of seasonal water deficit.

Figure 2 compares WDI seasonal dynamics recorded year 1 and year 3. While a similar amount of water is applied over season 1 and season 3, seasonal WDI is higher during season 3 (average WDI >60%). We speculate that applying larger irrigation volumes for 2 consecutive years has increased the depth of root absorption sites. These changes in root architecture probably contributed to the maintaining of higher seasonal WDI value (less water deficit) and a more efficient use of water.

2. Effect of sap flow profile on berry sugar accumulation

Research has demonstrated that relationships exist between berry compositional changes during ripening and seasonal vine water deficit variations (Deluc et al., 2009). The purpose of this treatment is to highlight the specific relationship between berry sugar accumulation dynamics and seasonal vine water use. Conclusions from this study aim at improving winegrower practices, such as irrigation, cover crop selection and canopy manipulation in order to modulate berry ripening. In this treatment, sap flow and water deficit index variations are collected in a non-irrigated vineyard, located in southern France, over 2 seasons (cv. Syrah). Thermal time (in °C.d) is computed by integrating hourly temperatures above a minimum temperature threshold set at 10°C.

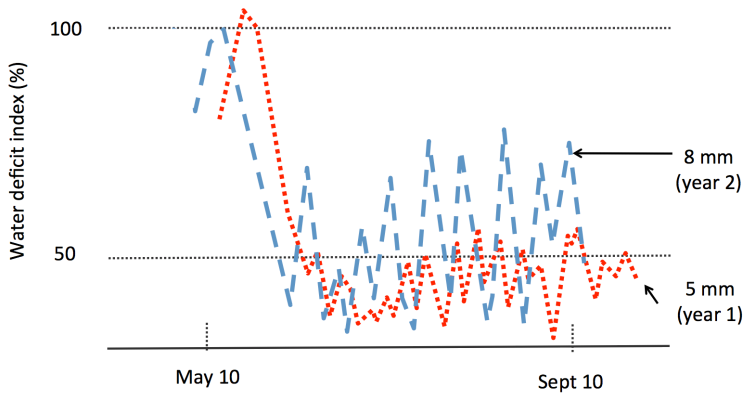

Figure 1. Comparison of water deficit index dynamics in response to increasing irrigation volume between year 1 (5 mm per irrigation) and year 2 (8 mm per irrigation).

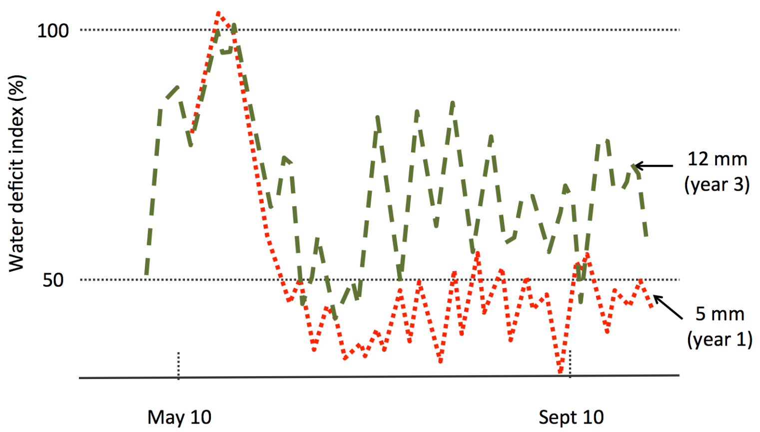

Figure 2. Comparison of water deficit index dynamics in response to increasing irrigation volume between year 1 (5 mm per irrigation) and year 3 (8 to 12 mm per irrigation).

Climatic context and WDI profile analysis

Prior to budbreak, year 1 and year 2 (November 1st- February 1st) are similar in terms of cumulated rain (130 mm for both years). Between February 1st and June 1st, cumulative rain is 210 mm for year 1 and 330 mm for year 2. From March 1st to September 1st, 1500 °C.d were accumulated for year 1 and year 2. Over the berry ripening period (900-1500 °C.d), vapor pressure deficit was greater than 3.6 kPa for 13 days during year 1; 0 day during year 2.

As expected during a drier year, Figure 3 shows that WDI reaches low values (< 40%) from 900 °C.d onward in year 1. Relative to the climatic demand, the level of plant available water is limited. Thus, seasonal WDI is relatively low, which also reduces photosynthetic activity. However, during a wetter year, WDI is constantly above 50%, which favors a higher photosynthetic activity in year 2.

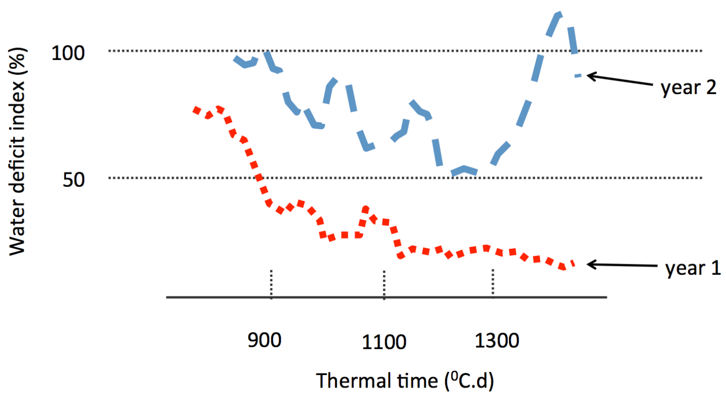

Figure 3. Comparison of water deficit index dynamics in a non-irrigated vineyard (year 1: less rain and higher VPD; year 2: more rain and lower VPD).

Berry sugar accumulation profile analysis

Two hundred berries were sampled at eight different dates over a same area of 50 vines, centered on sap flow monitored vines. Figure 4 shows the dynamics of sugar amount per berry. During year 1, as a low seasonal WDI is being recorded, initiation of sugar accumulation is late (after 1000 °C.d). The maximal amount of sugar per berry is reached late (after 1500 °C.d). In contrast, during year 2, as a high seasonal WDI is being recorded, initiation of sugar accumulation starts earlier (before 1000 °C.d). The maximal amount of sugar per berry is reached earlier (around 1300 °C.d) and is 20% higher than year 1. Similarly, maximal berry weight is 20% higher year 2 (data not shown).

Effect of WDI on sugar accumulation

When WDI is maintained below 50%, sugar accumulation is low. Most likely during year 1, a low water use reduces photosynthetic activity, which affects negatively active sugar accumulation in the berry. When WDI is maintained above 50%, sugar accumulation is high. Most likely a higher photosynthetic activity combined with a greater water use promote an earlier rate of berry sugar accumulation and a higher amount of sugar per berry.

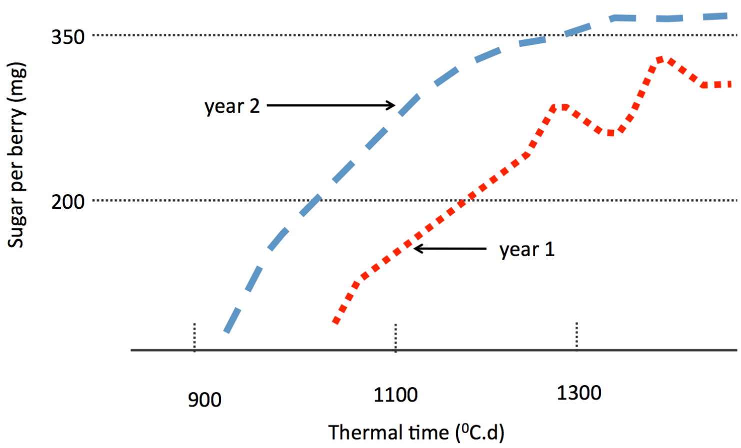

Figure 4. Comparison of berry sugar accumulation rate in a non-irrigated vineyard. (year 1: less rain and higher VPD; year 2: more rain and lower VPD).

3. Relationship between nitrogen uptake and sap flow

In the context of a dry winter, soil nitrogen mineralization rate can be reduced. Consequently, after a dry winter, even if soil moisture is no longer limited after the season start, vine nitrogen accumulation can be reduced (Mendez-Costabel et al., 2014). However, when soil moisture supply is limited early season, even after a wet winter, vine nitrogen uptake can also be reduced for lack of sufficient water uptake while the amount of nitrogen may not be limiting. Thus, when nitrogen deficit is diagnosed, it is difficult to distinguish whether a low nitrogen supply (following a dry winter) or a low soil moisture supply early season is the culprit. As both conditions can lead to a lack of nitrogen uptake, deciding which corrective action is best is challenging.

In this context, a joint analysis of sap flow and nitrogen accumulation can help discriminating between two situations likely to cause nitrogen deficit. As an illustration, we compared sap flow dynamics and nitrogen dynamics obtained in vineyard A and B, located in Napa, California (cv. Cabernet Sauvignon) over two consecutive years. Along sap flow variations; temporal variations in leaf nitrogen concentration were analyzed weekly. Leaf nitrogen readings were performed using leaf fluorescence method. Published guidelines were used to characterize nitrogen level as low, moderate or high (data not shown). Site A was diagnosed with low nitrogen year 1 and high nitrogen year 2. Site B was diagnosed with a high nitrogen year 1 and low nitrogen year 2.

Climatic context

Year 1 was a "drier" year as the amount of winter rain cumulated between Nov. 1st – March 1st was less than 380 mm. Year 2 was a "wetter" year and cumulated winter rain over the same period was greater than 750 mm. In site A, maximum K_{cb} was lower in year 1 (30%) compared to year 2 (40%) as more water available early season during year 2 stimulated the development of a larger transpiring leaf area. In site B, maximum K_{cb} was similar both years (50%). Growing degrees days are cumulated since March 1st.

WDI and Nitrogen accumulation profiles analysis

<u>*WDI profiles typical of vineyard site experiencing well-watered conditions early season.*</u>

In vineyard A, nitrogen deficit is observed year 1 during the period 400- 800 °C.d. Figure 5 shows that high water uptake is observed during that period, as indicated by high WDI values (>80%). Year 2, leaf nitrogen concentration is high, in spite of a moderate reduction in sap flow early season as indicated by lower WDI value. Thus, year 1, low nitrogen accumulation is not directly related to low water supply conditions. A reduction in the initial pool of available nitrogen early season is suspected to cause a low leaf nitrogen accumulation. We speculate that dry soil conditions during the winter have probably limited nitrogen mineralization rate and consequently the amount of nitrogen available early season. A nitrogen fertilization directly via a foliar spray is recommended as the corrective action. Interestingly, year 2 received more winter rain and a higher level of available nitrogen is expected early season. This probably lead to a greater leaf nitrogen concentration.

<u>*WDI profiles typical of vineyard site experiencing water deficit early season.*</u>

In vineyard B, nitrogen deficit is observed year 2 during the period 400- 800 °C.d. Figure 6 shows that a low water uptake is observed during that period, as indicated by low WDI values (<60% over 500-650 °C.d). Because a period of low water use co-occurs with low nitrogen accumulation, we speculate that early water deficit conditions have contributed to reducing nitrogen uptake, even if winter rain supply was high (i.e., more favorable to high nitrogen supply early season). Early season irrigation alone or combined with a fertilization through the irrigation line is recommended as the corrective action. Interestingly, during the "dry" year 1, vineyard managers applied 3 irrigations early season (400- 600 °C.d) to compensate for the low winter rain supply. Consequently WDI increased sharply around 500 °C.d and remains high (>80%) until 650 °C.d. High water use conditions are maintained during the period of nitrogen uptake. Nitrogen supply early season is not limiting and leaf nitrogen concentration is high.

By analyzing jointly nitrogen uptake and sap flow, plant nutritional diagnosis can be improved and lead to better-targeted practices.

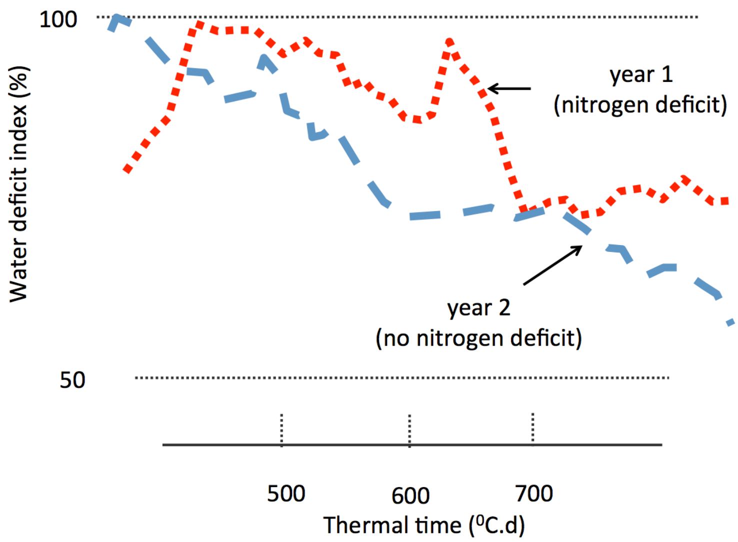

Figure 5. Vineyard A : High sap flow and low nitrogen is observed year 1. Foliar spray of nitrogen is recommended to correct nitrogen deficit.

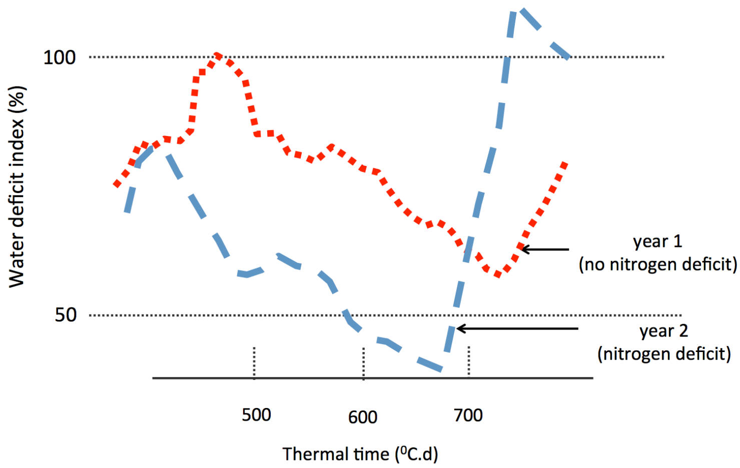

Figure 6. Vineyard B: Low sap flow and low nitrogen is observed year 2. Irrigation and possibly fertigation is recommended to correct nitrogen deficit.

CONCLUSIONS AND PERSPECTIVES

Sap flow is a fundamental tool to develop precision farming

Because it is a fundamental plant-based index, sap flow seasonal variations analysis is a good entry point to develop a holistic vineyard monitoring strategy in conjunction with other plant-based methods. Apart from irrigation, many practical decisions related to vine health and performance can be improved when interpreted within the framework of sap flow variations such as leaf area manipulation or fertilization decisions. Winegrowers have been using sap flow as a base line to track the impact of different farming strategies. In a context of more elevated temperatures, sap flow response analysis is critical to adjust practices in response to extreme climatic events such as more frequent heat waves or drier winters.

In the context of precision viticulture, sap flow response analysis is useful to legitimate new practices or to target specific areas according to vineyard spatial variability. Because it is a continuous measurement, sap flow is also useful for ground validation of other sensing approaches, which are not necessarily continuous. For instance, sap flow measurements can be combined with thermal imagery to evaluate the temporal stability of spatial indexes. Sap flow measurements can also be combined with fluorescence methods to evaluate the relationship between water deficit and other plant and fruit indexes such as nitrogen or fruit color accumulation. Compared to other vine water status monitoring techniques, sap flow offers a plant-based measurement, which does not rely upon indirect measurements or a complex conceptual framework (i.e., aerial pictures, environmental monitoring, modeling approaches, etc.…). As such, winegrowers can learn directly from observing the vines equipped with sap flow sensors and perform other plant-based measurements on or around the same vines. The knowledge generated from a few carefully selected locations can then be applied over larger areas where less information is available. One classic feedback from first time sap flow users under semi-arid climates is to learn that plant “look” is deceiving. The combination of visual cues with continuous vine water use monitoring teaches how to move away from traditional irrigation habits with confidence. As winegrowers develop trust in sap flow technology, other vineyard monitoring technologies are more easily adopted. As more data is collected from the same sampling areas, vineyard monitoring becomes more precise due to the synergies between different vineyard information sources.

Sap flow driven irrigation reduces water and energy use

In general, monitoring of vine water deficit with sap flow leads to a reduction in water use compared to traditional practices. As such sap flow technology deployment provides a great opportunity to incentivize a smarter use of irrigation water. Because it contributes to save water, sap flow driven irrigation is being tested by water and energy agencies. In 2014, the Metropolitan Water District of Los Angeles investigated the amount of water savings that could be obtained by adopting sap flow driven irrigation. Traditional and sap flow driven irrigations were applied side to side within the same vineyards to compare the amount of water used according to each strategy. Figure 7 shows the 3 California wine regions where trials were deployed to compare the two treatments over six vineyards. Figure 8 shows that the volumes of water use for irrigation are different for each site. However, despite site specific differences in total amount of water applied, sap flow driven irrigation strategies reduced the total amount of water by 60% on average compared to traditional irrigation strategies. Interestingly, average yields were higher by 15% in the sap flow driven irrigation (data not shown). In traditional irrigation treatments yield losses were observed as a result of berry dehydration before harvest. No significant differences were observed in total amount of sugar per berry between the two strategies. As sap flow treatments impose longer periods of drought, we speculate that vine water-use regulation mechanisms (such as mediated by ABA) may contribute to decrease berry susceptibility to dehydration pre harvest. In 2016 the California Energy Commission funded a 3 years project to assess the benefits of sap flow driven irrigation on water pumping energy over large scale vineyards (>300 acres). The project is currently on going and may contribute to further disseminate the benefits of sap flow use in viticulture and beyond.

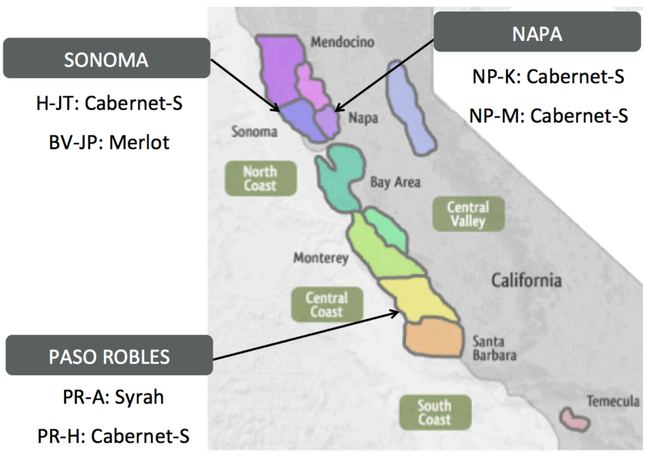

Figure 7. Location of sap flow experiments in the context of the 2014 water saving project (funded by the Metropolitan Water District of Los Angeles).

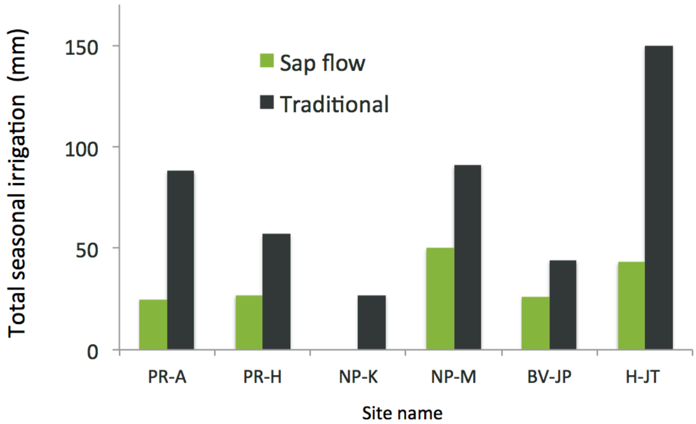

Figure 8. Comparison of water applied between various traditional and sap flow irrigation treatments (funded by the Metropolitan Water District of Los Angeles).

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