

State-of-the-art of tools and methods to assess vine water status

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ABSTRACT

Rising global air temperatures will lead to an increased evapotranspiration and altered precipitation pattern. In many regions this may result in a negative water balance during the vegetative cycle, which can augment the risk of drought and will require mitigation strategies. These strategies, ultimately, will mean the installation of irrigation systems in some winegrowing regions where vines were cultivated historically under rain-fed conditions and growers do not have many years of experience with vine water management.

This review aims to provide a state-of-the-art summary of the recent and most important literature on vine water assessment for monitoring and adapting vineyard management strategies to production goals in view of global warming. Plant, soil and atmospheric methods are reviewed, and their advantages and drawbacks are discussed. Recent advances in plant water status measurement reveal the limitation of traditional techniques such as water potential, particularly in the context of drought and high vapor pressure deficit and the discoveries regarding hydraulic and stomatal regulation. New technologies can integrate heterogeneous sources of information collected in the vineyard at different spatial and temporal resolutions. Such new approaches offer new synergies to overcome limitations inherent to plant water status measurement techniques obtained directly or indirectly from proxy measurements.

KEYWORDS

vine water statut, water potentiel

INTRODUCTION

Although 70 % of the Earth's surface is covered in water, of this only 2.5 % is freshwater and only 1 % is easily accessible because most of it is trapped in glaciers and snowfields (Siddique and Bramley, 2014). Worldwide, over 330 million ha of agricultural land are irrigated. This corresponds to around 20 % of the total farm land, and contributes to 40 % of the total food produced worldwide, due to higher productivity of irrigated land (<http://www.fao.org/nr/water/aquastat/data/glossary/search.html>). Irrigated agricultural production systems are the world's major consumer of fresh water, at around 60 % of total freshwater withdrawals and 80 % of total freshwater consumption (Siebert *et al.*, 2010, 2015). In viticulture, irrigation was historically limited to the so-called “new viticultural countries” such as Australia, Argentina, the USA and Chile, where a total of about 580,000 ha is irrigated, which corresponds to approximately 83 % of the total vineyard surface. In Argentina, for example, approximately 250,000 ha – almost the entire viticulture area – is irrigated. For almost 20 years, irrigation has also been developing rapidly in traditional European viticulture areas (Ojeda, 2007).

In a world where fresh water is a scarce resource, around 850 000 million people lack basic access to drinking water and 2.5 billion people do not have safe water at home (WHO, 2017), there is an urgent need to reduce the “water footprint” of irrigated crops (Cominelli *et al.*, 2009).

Global warming is likely to continue at its current rate and will lead to a temperature increases of at least 1.5°C between 2030 and 2052 (IPCC, 2018). The consequences will involve changes in precipitation patterns, more frequent heat waves, droughts and a general increase in evapotranspiration (ET) rates, leading to an increasingly negative water balance during the vegetative cycle (Schultz and Stoll, 2010; van Leeuwen and Destrac-Irvine, 2017). Consequently, there will be a growing need for irrigating agricultural crops to mitigate droughts, maintain a sustainable production and guarantee global food supply.

Viticulture and the wine industry are an important economic branch for many countries, represented in a wide range of extremely diverse climates all over the world and highly affected by global climate change at different scales.

The impact of warming on vine physiology, phenology, berry composition, wine quality and typicity is the subject of many scientific studies (Fraga *et al.*, 2012, 2013, 2014; Hannah *et al.*, 2013; Keller, 2010a; Mira de Orduna, 2010; Schultz, 2000, 2016; van Leeuwen and Destrac-Irvine, 2017; van Leeuwen *et al.*, 2013) and will not be addressed in this paper.

A grapevine needs between 300 and 600 mm of water in cool climates (Williams, 2014) and between 400 and 800 mm in hot climates (Williams and Baeza, 2007) during the vegetative cycle, which is highly dependent on cultivar, rootstock, training system, planting density, yield and seasonal temperature patterns. In most European winegrowing regions, vines are still cultivated under rain-fed conditions, also called “dry farming”, which is the strategy that induces the lowest possible blue water footprint. Hence, all cultural and agronomic strategies to mitigate the risk of drought should be considered before implementing irrigation.

Such strategies, as reviewed by Medrano *et al.* (2015), consist in decreasing total vineyard water consumption by the adaption of canopy management, training systems, planting density, cultivar and rootstock. For example, reducing planting densities in combination with a low leaf area training system such as the Gobelet/Vase or bush vine systems is an efficient way to reduce total vineyard water consumption and the reason why such systems were historically developed in very dry regions. However, in general such systems are low yielding and meccanization is limited, which can impact the economic success of producers (van Leeuwen *et al.*, 2019). Management of cover crops and mulching can contribute to reducing vineyard water consumption (Medrano *et al.*, 2015). The choice of plant material is a very powerful tool to adapt vineyards to drought, through the combination of drought-resistant rootstocks (Ollat *et al.*, 2016) and drought-resistant cultivars (Lovisolo *et al.*, 2016; Schultz, 2003).

Still, the increased frequency and severity of drought over the last three decades, mainly in Mediterranean viticulture areas, has required the installation of irrigation systems to maintain an economically sustainable production (FAO, 2016). Even in northern European viticulture regions, growers have faced periods of drought in recent years and vine water status assessment has become an increasingly important tool to

adapt agronomic practices and eventually monitor irrigation.

It is well known that a moderate plant water deficit can improve the partitioning of carbohydrates to reproductive structures such as fruit and control excessive vegetation. This led to improved water use efficiency, which demonstrates the intrinsic trade-off between carbon fixation and water loss (Boyer, 1970; Chai *et al.*, 2015; Chalmers *et al.*, 1981). This concept has particular importance in viticulture, where although the aim is a maximal biomass production or yield, fruit quality determined by a complex equilibrium of primary and secondary metabolites is more important and can be improved by water deficit (van Leeuwen *et al.*, 2009).

However, a severe water deficit can cause losses in quantity and quality, and can threaten the longevity of a vineyard by reducing reserves of perennial parts (Pellegrino *et al.*, 2014). It is also important to consider that water deficit does affect the availability and absorption of nitrogen, thereby reducing the synthesis of certain precursors of aroma compounds such as thiols and the amount of fermentable nitrogen in the must, which can cause fermentation problems (Helwi *et al.*, 2016; Peyrot des Gachons *et al.*, 2005).

Therefore, it is of great importance to assess vine water status as precisely as possible and to adapt agronomic practices according to production goals. In view of recent scientific advances regarding hydraulic segmentation, isohydric and anisohydric behavior of vines, many questions arise regarding traditional assessment methods and will be discussed subsequently.

The present review will address critically the most common and state-of-the-art systems and techniques that growers can use for vine water status assessment.

A subsequent paper will address the physiological and technological considerations to optimize irrigation systems.

METHODS FOR MONITORING VINE WATER STATUS

Choosing the most appropriate method(s) for measuring water status can be very different depending on the purpose: (a) practical management such as irrigation scheduling, quantification of the impacts of cultivation

practices or understanding the impact of water status on yield and quality potential; (b) understanding the mechanisms of water movement; (c) understanding the mechanisms involved in water stress effects on growth and physiology; or (d) identifying differences in drought tolerance for breeding or for selecting drought-tolerant genotypes

Only methods that are relevant for vineyard management decisions will be discussed here. Plant water status measurements can typically be divided into indirect, soil-based or atmospheric-based methods and direct plant-based methods, each having different benefits and drawbacks depending on the application.

1. INDIRECT METHODS

1.1. Soil-based methods

Soil-based methods directly determine soil moisture by either volumetric methods (water percentage in a given volume of soil) or by tensiometric methods (physical force holding water in the soil). There is a myriad of different sensor types and suppliers with different systems, some reading water suction directly and most using indirect measuring systems via electric currents. Among the most commonly used instruments are tensiometers and soil psychrometers to measure directly the capillary tension or energy with which water is withheld by the soil (Mullins, 2001). Examples of volumetric measuring systems are neutron moisture probes and capacitance sensors (Townend *et al.*, 2001), which are frequently used in a production context.

The main advantage of the sensors placed directly in the soil is to enable remotely a continuous and automated monitoring of soil moisture. A further benefit compared with plant-based methods is that soil water content can be monitored during the winter to assess the refilling of soil water capacity. Such permanently installed sensors are widely used for irrigation monitoring of annual crops on shallow and homogeneous soils as well as in greenhouses (Müller *et al.*, 2016; Pardossi *et al.*, 2009). However, in the specific context of viticulture, the use of soil moisture sensors to monitor irrigation has several drawbacks.

For very heterogeneous plots, which are often encountered in viticulture, ideally the soil needs to be fully mapped prior to placement and subsequently the number and location of each



FIGURE 1. A vineyard monitored with an EC system. There is a sonic anemometer at the front, and tools for ET_{ref} measurements (pyranometer, relative humidity, windspeed, temperature, rain gauge), for other atmospheric recordings (solar panels, data logger for soil moisture sensor, heat plate) and data transmission box in the background.

sensor needs to be adjusted according to the soil heterogeneity. In traditional winegrowing regions, producers have a high number of different parcels that can be diverse in terms of soil properties, requiring a high number of sensors and thereby representing a significant financial investment. In many regions, vineyard soils do have a very high gravel and stone fraction, which makes it almost impossible to install soil sensors.

Furthermore, soils sensors require regular maintenance and have often a rather limited life span, in particular in viticulture where frequent passages with heavy machinery for tillage operations, mowing, and other soil-related interventions increase the risk of damage for the often rather fragile sensors.

Due to the immobility of sensors once they have been placed, soil moisture can only be assessed at one very small spot in a given vineyard plot, so it doesn't reflect well horizontal and vertical spatial variability of soil moisture perceived by the deep root system of vines. As such, assessing precisely the amount of water available to plants will be challenging, particularly considering the occurrences of water redistribution from regions of high soil moisture to roots in dry soil (Smart *et al.*, 2006a). Furthermore, deep vine rooting, which depends on soil type, limits the possibilities of soil-based methods. As long as the vine has access to water in deeper soil layers, which is not necessarily sampled by the soil-based methods, there is no water deficit.

There can be situations where such sensors can be appropriate for viticulture, for example when soil and microclimate are very homogeneous over large vineyard plots. However, in general, it remains fairly complex to extrapolate vine water status from soil moisture measurements (Lavoie-Lamoureux *et al.*, 2017) as plant water status is not simply or directly connected to soil moisture content.

1.2. Atmosphere-based methods

Vine water consumption can be estimated by assessing total vineyard evapotranspiration (ET) using atmospheric measurements within the vineyard. A variety of techniques are available to assess system-level ET, without distinguishing ET between individual components such as vine transpiration or soil evaporation. Estimation of vineyard actual evapotranspiration (ET_a) can be obtained with measurements taken using the eddy covariance method and the Bowen ratio energy balance method (Li *et al.*, 2008).

The principle of ET_a estimation from atmospheric measurements is based on the total energy balance. Net radiation (R_n) must be in balance with the ground heat flux density (G), sensible heat flux density (H), latent heat flux density (LE), and other less significant energy reserves and producers (such as biomass and photosynthesis). The latter, however, can be neglected (Shapland *et al.*, 2012). A simple mathematical description of energy partitioning at the Earth's surface can be thus summarized as:

$$R_n - G - H = LE \quad (\text{Eq. 1})$$

LE can be divided by the latent heat of evaporation (L) to obtain the mass flux density of water vapor which can be the actual ET_a (Eq. 2) :

$$ET_a = LE/L \quad (\text{Eq. 2})$$

Accuracy in ET estimation from Eqs (1) and (2) depends upon the results obtained from the calculations of R_n , G and H (Hu *et al.*, 2018).

R_n can be directly measured in horizontal terrains and needs to be corrected according to terrain slope to account for inclination and exposition (Georg *et al.*, 2016).

G can be measured using soil heat flux plates and temperature sensors. These plates consist of thermopiles that measure the temperature gradient across the plate material, which has a known thermal conductivity. G measurement is very important, but it is difficult to estimate precisely because of row shade variation during the day that affects soil heat flux continuously.

H is the most difficult component of the surface energy balance to quantify because it is split between the three compartments: soil, vine and cover crop. It can either be measured by the eddy covariance method, the Bowen ratio method or alternatively with the surface renewal (SR) method, as exposed subsequently.

Eddy covariance is the standard method for determining energy and substance fluxes. It measures directly carbon, water, and heat flow between plant communities and the atmosphere and is considered, in the field of micrometeorology, to be the most efficient method for measuring such interactions (Baldochi, 2008; Liang *et al.*, 2012).

The Bowen ratio energy balance is another micrometeorological method for estimating ET_a and has also been used to estimate vineyard evapotranspiration over the whole growing season (Yunusa *et al.*, 2004; Zhang *et al.*, 2008). However, these techniques are complex and require expensive sensors (Drexler *et al.*, 2004), are mainly used for research purposes, and are not suitable for practical water status assessment or irrigation monitoring.

The SR method consists in analyzing temperature changes in coherent air parcels that interact directly with the crop surface (Kyaw Tha Paw *et al.*, 1995). Crop leaf surface properties are influenced by parameters such as row spacing, trellising system and architecture, and

will impact the distribution of energy sources within the canopy. Thus, H estimation is directly affected by vineyard and canopy architecture, creating uneven heating of air parcels (Carrasco-Benavides *et al.*, 2014; Snyder *et al.*, 1996; Spano *et al.*, 2000). Accuracy in H measurement is also affected by vine phenological stages, intrinsic vineyard specificities (spacing, row orientation, row height, row width) or spatial variabilities. For instance, comparing two Californian vineyards, Kustas *et al.* (2018) found that larger H values were measured during the growing season when leaf area and irrigation are reduced. Knipper *et al.* (2018) showed that land surface temperature variability increases with increased vineyard soil heterogeneity, which also complicates H measurements. Consequently, to account for measurement biases, the SR method must be calibrated against other methods such as eddy covariance (Poblete-Echeverría *et al.*, 2014). Comparing the SR method against eddy covariance to quantify H at different phenological stages in a Chilean vineyard showed that the SR method underestimated (by around 9 %) the fraction of water used for transpiration (i.e. the ratio $LE/(H+LE)$) around fruit set, and overestimated this (by around 12 %) around véraison (Poblete-Echeverría *et al.*, 2017).

Inter-row cover crops are an important and complex contributor to ET_a . Their implementation depends upon climate, water availability, soil properties, variety and production goals and can be over the whole vineyard surface or alternating every second row, and can be permanent or seasonal. Because such vineyard specific practices modulate the contribution from each compartment to total vineyard ET_a , their partitioning is complex and is currently the topic of much research (Jiao *et al.*, 2018). Several approaches can be used to partition evapotranspiration between distinct compartments, as reviewed by Kool *et al.* (2014, 2016).

In summary, the contribution of individual compartments (vine, bare soil and inter-row cover crop) to ET_a varies as a function of growing season. During periods of low vine leaf surface, bare soil evaporation (E) and cover crop transpiration (T) are the main contributors to ET_a . During that period ET_a is highly dependent on cover crop type, growth and management practices (such as mowing or tilling). The partitioning between E and T is controlled by seasonal dynamics of cover crop and vine leaf

area, affecting the leaf area index (LAI) as reported by Kustas *et al.* (2018). In general, the ratio T/ET_a increases from bud break until maximum vineyard LAI is reached, typically a few weeks after flowering. T/ET_a gradually declines toward harvest as soil moisture content decreases. T/ET_a finally re-increases in late autumn as cover crop rebounds. Using an atmosphere-based method to improve vineyard irrigation strategies is a promising approach but requires a careful partitioning of ET_a between vine transpiration and other compartments.

1.3 Water balance methods

Soil water balance calculations are indirect methods to assess vine water status. With such methods the total amount of transpirable soil water (TTSW) or its fraction (FTSW) over the soil profile is estimated, using a water balance approach in which the change in soil moisture over a period is given by the difference between the inputs (irrigation plus precipitation) and the losses (runoff plus drainage plus evapotranspiration) (Jones, 2004, 2007; Lebon *et al.*, 2003). TTSW is observed at field capacity and depends on effective rooting depth and soil composition, which determines the fraction of non-available soil water at the wilting point. TTSW is deduced from total soil water at field capacity minus the non-available soil water (Campos *et al.*, 2016).

TTSW denotes the starting point for the model when the soil is at field capacity. The model keeps a daily update of soil water content in which the remaining soil transpirable water on any day (TSW_d) is calculated as:

$$TSW_d = TSW_{d-1} + Rain_d + I_d - Runoff_d - ES_d - T_{crop,d} \quad (\text{Eq. 3})$$

where TSW_d = an estimate of the total available water on date d , R = rain, I = irrigation, ES = soil evapotranspiration _{d} (with or without covercrop), and T_{crop} = transpiration from the vine canopy.

$$FTSW_d = TSW_d / TTSW \quad (\text{Eq. 4})$$

The complex implementation of cover crops in such water balance models has been carried out successfully (Celette *et al.*, 2010) and has been used to simulate vine water stress indices for non-irrigated conditions (Gaudin *et al.*, 2014). However, under irrigated conditions, implementation of cover crops in water balance models remains challenging due to complex interactions between soil management practices and the distribution of grapevine root systems (Linares Torres *et al.*, 2018). Campos *et al.* (2016)

estimated the TSW by combining measured evapotranspiration using eddy covariance and a water balance over three commercial vineyards located in southern Europe. Their findings show that model performance is highly dependent upon the estimation of TTSW and that most reliable values are obtained under severe water stress conditions or during seasons with low water availability. Otherwise, there is a high risk of overestimating vine water use.

More complex models, combining remote sensing information with soil water balance, require a precise estimation of the root zone water-holding capacity represented by the parameter TTSW. The great variability in root depths and root distribution of grapevines makes it difficult to establish TTSW. Deep roots in vineyards can reach up to 6 m in depth as reported by Branas and Vergnes (1884). Other authors have reported root extraction of soil water at depths greater than 2 m in vineyards (Campos *et al.*, 2016; Pellegrino *et al.*, 2004). In irrigated vineyards, Smart *et al.* (2006b) concluded that, on average, the root density of different varieties of vine rootstocks is concentrated in the first 60 cm of soil, representing 63 % of the total root biomass.

To tackle difficulties related to TTSW and T_{crop} estimations, new approaches have been tested to calibrate and use vine water balance models in conjunction with aerial and atmospheric data. At a plant scale, vine water balance models rely on the parameterization of a basal crop coefficient, K_{cb} . At a vineyard scale, the water balance model relies on parameterization of a general crop coefficient, K_c computed from K_{cb} as:

$$K_c = K_s K_{cb} + K_e \quad (\text{Eq. 5})$$

where K_s is a dimensionless ‘stress’ coefficient whose value is dependent on available soil water and K_e is a coefficient that adjusts for increased evaporation from wet soil following rain or irrigation (Allen and Pereira, 2009). Direct measurements of K_c can as well be obtained in the vineyard using lysimeters (Munitz *et al.*, 2016).

Using spatial imagery and eddy covariance measurements, Xia *et al.* (2016) found that daily water use estimates can be significantly improved through the partitioning of water losses between the soil/cover crop inter-row and vine canopy elements. To determine the extent to which vines contribute separately to ET_a , the dual K_c method uses the basal crop coefficient

(K_{cb}) defined as the ratio of the crop transpiration (T_{crop}) over the reference evapotranspiration (ET_0), when the soil surface is dry but transpiration is occurring.

T_{crop} can be measured directly using sap flow gauges and results show that actual K_{cb} values are generally lower than those published in the literature (Lascano *et al.*, 2016a; Poblete-Echeverría and Ortega-Farías, 2013; Zhang *et al.*, 2011). Thus, vineyard water use models based on the dual method can be improved with accurate T_{crop} measurements. This increased accuracy led to an increasing trend in using the dual Kc method over the single Kc method in general agriculture (Pereira *et al.*, 2015) on a global scale as initiated by NASA (<https://ecocast.arc.nasa.gov/simsi/>) and recently also in viticulture (Phogat *et al.*, 2017).

When T_{crop} cannot be measured directly, K_{cb} could potentially be estimated from high time resolution satellites imagery. However, due to the pixel size of satellite images (close to 1 m) a precise separation of soil or cover crop from canopy is still impossible (Helman *et al.*, 2018), thus direct T_{crop} determination in situ remains crucial.

1.4 Strengths and weaknesses of using reflectance values to derive crop coefficients

Balbontín *et al.* (2017) used aerial pictures to determine crop coefficients in irrigated table grape from reflectance-based indices (NDVI). They applied the K_{cb} -NDVI relationship developed by Campos *et al.* (2010) and obtained a maximum K_{cb} that was greater than the K_{cb} proposed in the FAO-56 manual (Allen *et al.*, 1998).

Similarly, Calera *et al.* (2017) discussed how remote sensing imagery could be leveraged to improve ET_a modeling using relationships between K_{cb} and a vegetative index obtained from reflectance measurements. Other authors found that the main advantage of reflectance-based models is to offer an estimate for the maximum ratio of T_{crop} over ET_0 for a non-water stressed canopy. For wine grape production, however, irrigation scheduling seeks to maintain a balance of moderate water deficit during the growing season, mainly for quality reasons (detailed in Scholasch and Rienth, 2019), and thus one cannot assume that maintaining actual T_{crop} is an optimal irrigation strategy. As such, knowledge of the desired water stress level and

further calibration of the methodology for evaluating irrigation requirements are required.

Calera *et al.* (2017) highlight that it remains technically challenging to estimate the evaporation component from soil and such models tend to overestimate T_{crop} under conditions of water shortage. The authors highlight that the relationship between K_{cb} and reflectance value varies with stomatal control. As stomatal control can be regulated by environmental factors others than soil moisture deficit (Scholasch and Rienth, 2019), direct practical application for irrigation remains technically complex.

1.5 Summary: water balance models, plant vs. vineyard scale

Fusing atmospheric measurements with water balance models and remote sensing measurement is a promising approach to estimate vineyard ET_a , but still requires calibration with direct plant-based measurements in the vineyard. When alternative methods such as SR are used to compute LE or ET_a , underestimations and overestimations can be expected over the same growing season. This illustrates the challenge to estimate K_{cb} from indirect measurements during the growing period, as reported by Kool *et al.* (2016).

In conclusion, the main challenges in implementing a water balance model under irrigated condition are related to the calibration of two parameters: a reliable estimate of TAW over a non-uniform surface for a deep rooting species and a reliable estimate of K_{cb} .

2. DIRECT OR PLANT-BASED METHODS TO EVALUATE WATER STATUS

2.1 Visual observation

One of the simplest ways to assess the water status of a vine is by direct visual field observation. The slowing down of vegetative growth is among the earliest responses of a plant sensing a limiting water supply, thus the slackening of shoot growth can be noticed primarily by observing the apical meristem or apex of vines. This can be carried out in a systematic way, where 30–50 apices per plot are visually observed and classed into three different groups: a straight-growing apex, where the first expanded leaf is small and well beneath the apex; then a slowing down of growth with the first expanded leaf covering the apex; until

where the apex has dropped and shoot growth has completely ceased (Rodriguez-Lovelle *et al.*, 2009). A further and sometimes even earlier indicator are tendrils that in non-water stressed vines are turgid and expand well beyond the shoot tips but moderate water deficit leads to their wilting and subsequent abscission when water deficit becomes severe (Keller, 2010b)

2.2 Pressure chamber

Vine water potential (Ψ) is the suction pressure or the negative pressure necessary for the plant to extract water from the soil. To maintain a continuous water flow through the xylem from the roots to the leaves, where it is transpired through the stomata, the water potential inside the different parts of the vine needs to be lower than the soil water potential. If the quantity of available soil water decreases, the vine decreases its water potential to ensure water supply for photosynthesis, vegetative and generative growth. Vine water potential is thus a good proxy for plant available soil water and to assess water stress of the vine.

Plant water potential can be assessed by the pressure chamber, which was developed in the 1960s (Scholander *et al.*, 1965) and is still among the tools most used to evaluate plant water status in viticulture (Choné *et al.*, 2001; Pellegrino *et al.*, 2005; Sibille *et al.*, 2007; van Leeuwen *et al.*, 2009; Yuste *et al.*, 2004), as in many other crops (Rodriguez-Dominguez *et al.*, 2018)

The mode of operation of this tool is rather simple. A leaf and petiole or stem segment is placed inside a sealed chamber. Pressurized air is slowly released into the chamber. As the pressure increases onto the sample (leaf), xylem sap will be forced out and will be visible as a drop at the cut end of the petiole. The pressure applied until the appearance of the drop is equal and opposite to the water potential of the sample. Due to its portability, mechanical simplicity and robustness, combined with low maintenance and being relative cheap, pressure bombs are the predominant method for water potential measurements in viticulture. According to measuring time and protocol, different plant water potentials can be assessed.

a) **Leaf water potential Ψ_{leaf}** is the simplest measure, usually taken at midday on a well-exposed adult leaf. The drawback of this very quick assessment during a convenient time of the day is that homeostasis between leaf water

potential and soil water potential underlies rapid temporal fluctuations as a function of environmental conditions (such as passing clouds). It is also highly dependent on the microclimatic environment of each particular leaf (Jones, 2004). Moreover, vines might have an an- or isohydric behavior, and limit variations in water potential of their leaves by stomatal regulation, which is currently debated and more discussed in (Scholasch and Rienth, 2019) (Charrier *et al.*, 2016; Schultz, 2003; Simonneau *et al.*, 2017). This makes the interpretation of leaf water potential as an indicator of irrigation need often unsatisfactory. Nevertheless, in spite of the concerns with the use of leaf water status as outlined above, it has been reported that leaf water potential can, when corrected for diurnal and environmental variation or under very stable climatic situations, provide a sensitive index for irrigation control (Williams and Araujo, 2002).

b) **Stem water potential Ψ_{stem}** is determined by enclosing a leaf in a plastic bag surrounded by aluminum foil for 45–120 min. This way, the leaf stops transpiration and will equilibrate its water potential with the water potential in the stem (Garnier and Berger, 1985; Greenspan *et al.*, 1996). Historically, stem water potential assessment has been presented a way of obtaining whole vine water status during the day and is alleged to be highly correlated with vine transpiration (Choné *et al.*, 2001). It is an accurate measure for revealing small water deficits, or water deficits on soils with heterogeneous humidity in interaction with vine rooting. Stem water potential is generally measured between 13.00 h and 16.30 h, when values reach the minimum. Stem water potential is stable and sensitive as opposed to leaf water potential, which means that four, five or six bagged leaves are enough to obtain correct information on a vine water status in homogeneous situations.

c) **Predawn leaf water potential Ψ_{PD}** is usually measured just before sunrise on adult leaves. It is assumed that plant and soil come into equilibrium overnight and Ψ_{PD} reaches the daily maximum level predawn (Améglio *et al.*, 1999; Klepper, 1968). Thus, the predawn or base water potential is a good reflection of the soil moisture level and can serve as a measure of static water deficit in vines. Ψ_{PD} will be in homeostasis with the most humid soil layer independently from its thickness, thus the absolute available water content in the soil could be smaller than expected

by the measured value (Améglio *et al.*, 1999). It has been shown that the full equilibrium between soil and plant water potentials in northern conditions is often not reached by dawn in summer, because of the shortness of the darkness period and probable night-time transpiration in the case of high atmospheric vapor pressure deficit (Sellin, 1999). Ψ_{PD} , and Ψ_{stem} are the most widely used water potentials in ecophysiological studies and industry (Dayer *et al.*, 2017; Etchebarne *et al.*, 2009; Ojeda, 2007; Ojeda *et al.*, 2001, 2002; Prieto *et al.*, 2010; Sibille *et al.*, 2007; Spangenberg and Zufferey, 2018; van Leeuwen *et al.*, 2009; Zufferey *et al.*, 2017, 2018), with Ψ_{stem} considered by some authors as showing the best correlations with vine transpiration (Choné *et al.*, 2000, 2001). However, this is challenged by others (Charrier *et al.*, 2016; Hochberg *et al.*, 2017; Santesteban *et al.*, 2011).

For practical reasons (simple, fast, convenient time of the day) growers use often Ψ_{leaf} which can give satisfying results, in particular under very stable environmental conditions where, Ψ_{PD} , Ψ_{stem} and Ψ_{leaf} can represent equally viable methods of assessing vine water status (Sibille *et al.*, 2007; Williams and Araujo, 2002)

Many water deficit studies have been conducted with different varieties, soil types, climates and management systems to evaluate vine physiological responses and consequences on berry quality and yield (Scholasch and Rienth, 2019). Those studies helped to define commonly accepted water deficit thresholds, which need to optimize quality and yield according to production aims (Ojeda, 2007; Romero *et al.*, 2010, 2013; Sibille *et al.*, 2007; van Leeuwen *et al.*, 2009; Zufferey, 2007), and the corresponding values are detailed in Table 1.

The duration of water potential measurements, including repetitions to account for technical, biological and soil variability, are time-consuming for growers with a high number of heterogeneous plots and thus represent a major inconvenience. Furthermore, the simple weight of the pressure chamber can make it difficult to conduct measurements on steep slopes and in terraced vineyards. Another major constraint in the use of vine water potential is the high measurement frequency required over the cropping seasons, due to their short validity after a rainfall event (Williams and Araujo, 2002; Yuste *et al.*, 2004).

However, recent published studies on hydraulic segmentation on different plant organs raised important questions about the interpretation of water potential measurement of leaves under extreme conditions, such as high VPDs and/or following cavitation events caused by more marked water stresses. The hydraulic vulnerability segmentation hypothesis that was recently re-addressed by several studies stipulates that distal portions of the plant (leaves, shoots) are more vulnerable to embolism than branches or trunks (Charrier *et al.*, 2016; Choat *et al.*, 2019; Johnson *et al.*, 2016). For instance, Charrier *et al.* (2016) showed that xylem embolism (or cavitation) is not reversible when root water potential is negative, which has already been shown in trees (Choat *et al.*, 2019). Grapevine embolism repair only occurs when root pressure becomes positive, which typically occurs during winter (Blackman *et al.*, 2019)

Watering cannot bring back vine T_{crop} to its maximum once cavitation has occurred. However, water potential may still increase after irrigation and reach the same values as before cavitation occurred. Thus, after a severe heat wave, a major loss of hydraulic conductivity could occur unnoticed by a winegrower who schedules irrigation based on water potential measurements (Charrier *et al.*, 2018).

Charrier *et al.* (2016) have shown that at -10 to -15 bars of Ψ_{stem} the loss of hydraulic conductivity can range between 0 % and 80 %. Thus, the hypothesis that vine transpiration and water potential are related is not always true (loss of hydraulic conductivity is not properly reflected by Ψ_{stem} or Ψ_{leaf}).

Observations in field studies support results from Charrier *et al.* (2016) when sap flow measurement and water potential measurement were performed on the same plants before and after heat waves. Highly negative water potential values no longer correlated with high sap flow values under such conditions (Scholasch, 2019). This will also mean that due to hydraulic segmentation the loss of hydraulic conductivity will not be revealed by the water potential assessment and needs to be taken into account in hot regions where the daily maximum VPD could stay above -4kPa for up to 40 days. The before-mentioned phenomenon, which is directly related to the loss of hydraulic conductivity, should have an increasing importance for water use modeling and irrigation

scheduling, particularly in the context of drought.

2.3 Carbon isotope discrimination

Two different stable carbon isotopes of CO₂ are present in the world atmosphere, with ¹²C being highly predominant one over ¹³C (Craig, 1953). ¹²C is preferentially picked up by the enzymes involved in photosynthesis (Farquhar *et al.*, 1980). This process is called isotope discrimination. Under water stress conditions, this discrimination is less severe, and sugars produced during water deficit situations contain more ¹³C compared to those produced when plant water status is not limiting. Hence, an index called δ¹³C, based upon ¹³C/¹²C ratio in grape sugar, can be used as an integrative indicator of water deficit experienced by vine during grape ripening. δ¹³C is expressed compared to a standard and ranges from -27 p. 1000 (no water deficit) to -20 p. 1000 (severe water deficit stress) (Gaudillere *et al.* (2002). This index shows a very good correlation with plant water potentials, measured with the pressure chamber (Gaudillere *et al.*, 2002; Spangenberg and Zufferey, 2018). Obviously, it can only be performed at the very end of the growing season and is therefore not well-adapted for day-to-day irrigation or agronomic management. It represents however a very valuable tool to evaluate agronomic measures and irrigations strategies of past seasons and can, as such, help to optimize and adapt future strategies (van Leeuwen *et al.*, 2009). Furthermore, this method permits a fine-scale mapping of vine water status within a vineyard plot as a function of sampling density (Herrero-Langreo *et al.*, 2013). It is also a useful tool for scientific studies (Spangenberg and Zufferey, 2018; van Leeuwen *et al.*, 2009) where it can be used not only to evaluate water stress of past seasons but also as a good proxy for integrated water use efficiency (WUEc) throughout the

season (Romero *et al.*, 2014). In addition, nitrogen deficit does apparently have a discriminatory effect on ¹²C incorporation via carboxylation (Jin *et al.*, 2015)

2.4 Stomatal conductance and leaf gas exchange measurements

Stomatal closure is among the most relevant and earliest physiological responses of the plant to water stress. The measurement of stomatal conductance (g_s) has been identified in grapevine as a suitable parameter to detect the degree of water deficit (Cifre *et al.*, 2005; Flexas *et al.*, 2002; Loveys *et al.*, 2000; Urban *et al.*, 2017). g_s is measured by evaluating either the water vapor diffusion from the leaf to a humidity sensor using a porometer, or by measuring both water and CO₂ diffusion from the leaf according to their infrared absorption wavelength using an infrared gas analyzer (IRGA). Porometers measure the diffusion of water vapor out of stomata with a humidity sensor housed in a leaf cup, which can be clamped onto a leaf. The air in the cup is dried to a predetermined humidity, and the time required for transpiration to bring the humidity up to a predetermined point is recorded (Bowling, 1989; Wallihan, 1964). This time interval is then used to determine transpiration rate and stomatal conductance. Porometers are highly dependent on frequent calibration procedures and measurements are often biased by differences between leaf and atmospheric temperatures (Pearcy *et al.*, 2000) and are thus gradually replaced over the years by IRGAs due to their higher reliability in terms of sensibility and accuracy (Ciccarese *et al.*, 2011). Such tools are rather expensive and sometimes complex to use and require regular calibrations.

2.5 Sap flow based measurement

Sap flow is the movement of fluid inside the xylem from the roots to the stems and leaves, where it is transpired through the stomata. Sap

TABLE 1. Water potential values (Ψ), stomatal conductance (g_s) and δ¹³C. Adapted from Carbonneau (1998), Lovisolo *et al.* (2010, 2016) and van Leeuwen *et al.* (2009).

	Ψ _{PD} (MPa)	Ψ _{Stem} (MPa)	Ψ _{Leaf} (MPa)	g _s (mmolH ₂ O.m ⁻² .s ⁻¹)	δ ¹³ C
No water deficit	> -0.2	> -0.6	> -0.9	> 500	< -26
Mild water deficit	-0.2 to -0.3	> -0.6 to -0.9	-0.9 to -1.1	200 to 500	-24.5 to -26
Moderate water deficit	-0.3 to -0.5	-0.9 to -1.1	-1.1 to -1.3	~150	-23 to -24.5
Moderate water deficit to severe water stress	-0.5 to -0.8	-1.1 to -1.4	-1.3 to -1.4	50 to 150	-21.5 to -23
Severe water stress	< -0.8/0.9	< -1.4	< -1.4	< 50	-21.5

flow is essential to maintain the hydraulic continuum between the soil, plant and the atmosphere. Monitoring sap flow dynamics of plants can thus provide fundamental information of plant hydraulic function or dysfunction in a given environment (Steppe *et al.*, 2015). Sap flow measurements can be used to monitor vine water status and are performant tools to manage vineyard irrigation (Eastham and Gray, 1998; Ginestar *et al.*, 1998; Pons *et al.*, 2008). Various methods exist to estimate sap flow and are described below.

a) **Thermal dissipation probes method.** Invented by Granier (1985), the method uses thermal dissipation probes inserted as needles into the vine. The system comprises a continuous heated needle and a reference needle, both containing a thermocouple and is based on the principle that the temperature difference between heated and reference needle declines when sap flow increases. However, Vergeynst *et al.* (2014) showed that circumferential and radial variation of sap flux density can lead to both under- and overestimations of sap flow. Furthermore, sap flux density can be underestimated when the heated needle is in contact with non-conducting tissues, for example dead biomass from pruning wounds. Therefore, the thermal dissipation probe method is not suitable for commercial use.

b) **The stem heat balance method.** To circumvent the mentioned limitations of the thermal dissipation probes, due to the needle intrusion into the stem of vines, another sap flow sensor design consists of a heated sleeve wrapped around the stem as described by Lascano (2000) and Lascano *et al.* (2016). Heat is provided uniformly and radially across the stem section; the sleeve is flexible and maintains a snug fit between the stem and thermocouple during stem diurnal contractions (Figure 1). Sensors can be applied over stems slightly bent or even when 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. The combination of vine transpiration and soil evaporation measurements using micro lysimeters leads to an estimated vineyard ET_a very close to ET estimated by the Bowen ratio energy balance method, as reported by Zhang *et al.* (2011). Thus, results suggest that the stem heat balance is a reliable method to compute vine transpiration separately from the other

components of ET. For those reasons the selection of non-intrusive sap flow sensors has been successfully adopted as a practice to drive irrigation strategies (Scholasch, 2018).

CONCLUSION

Global warming will increase the risks of drought periods and threatens a commercially sustainable wine production in many growing regions. Several mitigation strategies, such as the adaptation of training systems, planting density, plant material and rootstocks exist to sustain a sustainable and quality-oriented viticulture even under very dry conditions and should be considered before implementing irrigation

However, from an economical point of view this is often not possible and will urge many winegrowers to install irrigation systems. The assessment of vine water status to adjust management practices will become increasingly relevant, in particular in regions where growers do not have any experience with such practices. The assessment of plant water status by water potential measurements remains a quick, easy, and relatively cheap and direct method still widely used in the industry. However water potential measurements as a sensitive index for irrigation control can be challenging due to the effect of environmental fluctuations such as, for example, vapor pressure deficit variations that require correction of leaf water status (Santesteban *et al.*, 2011), which ideally should be varietal dependent (Scholasch and Rienth, 2019). Furthermore, important questions arise regarding the consequences of the recently reported hydraulic segmentation between perennial and annual parts and its influence of the in situ assessment of xylem sap water potential (Charrier *et al.*, 2016; Choat *et al.*, 2019; Johnson *et al.*, 2016). In fact, when simulating transpiration rate under water deficit, Albasha *et al.* (2019) reported that simulation of shoot hydraulic structure is essential to scale-up the gas exchange rate from a leaf scale to a canopy scale.

The measurement of vine transpiration separately under field conditions and throughout the growing season with the stem heat balance method overcomes the limitations of interpreting water potential when hydraulic segmentation or cavitation occurs. Sap flow variations directly reflect the effects of environmental stresses on plant hydraulic conductance variations and can



FIGURE 2. A sap flow sensor installed in the vineyard.

be used to compute K_{cb} . Consequently, measurement of vine transpiration is useful to calibrate vine water balance models using a dual approach.

Modeling approaches, coupling direct plant-based methods with indirect atmospheric measurements and aerial imaging methods are promising to compute separately the contribution of each compartment to ET and to develop an irrigation strategy based on the decline of the vine transpiration/ET₀ ratio. The need to fuse direct plant-based methods with indirect methods has been highlighted in recent literature, such as Kustas *et al.* (2018) who showed that T/ET₀ estimates obtained by merging atmospheric measurements with remote sensing imagery require independent measurements such as vine transpiration using sap flow gauges to determine vine water use and stress level, which directly impact yield and fruit composition. From there, new analytical methods combining data fusion processing package and machine learning algorithms with direct and indirect measurements of vineyard ET are yielding successful results (Alfieri *et al.*, 2018; Andújar *et al.*, 2019; Helman *et al.*, 2018; Prueger *et al.*, 2018; Romero *et al.*, 2018; Semmens *et al.*, 2016) and could be promising tools for wine water status assessment and irrigation monitoring in the future.

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