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Review

AN OVERVIEW OF VINE WATER STATUS ASSESSMENT

UMA PERSPETIVA DA AVALIAÇÃO DO ESTADO HÍDRICO DA VIDEIRA

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SUMMARY

In regions influenced by the Mediterranean climate, the distribution of rainfall is uneven throughout the year, with rainfall concentrated in winter and hot, dry summers, which is being boosted by climate change towards a worsening of this situation. Due to the high socioeconomic relevance of viticulture in these regions, monitoring the vine water status is extremely important. Although vineyards are typically a rainfed crop, water stress can result in quantitative and qualitative production losses, and irreversible damage to plants. The complexity of grapevine's physiological response to water availability can be measured through indicators, which quantify the degree of stress the plants are under, and thus decisions can be made on this basis. Therefore, this work describes the main water stress indicators used in viticulture, as well as the particularities of each one and the relationship between them, contributing to a better understanding.

RESUMO

Nas regiões influenciadas pelo clima Mediterrânico, a distribuição da precipitação é irregular ao longo do ano, com chuvas concentradas na estação de Inverno e Verões quentes e secos, algo que está a ser potenciado pelas alterações climáticas, que apontam no sentido de um agravamento desta situação. Devido à elevada relevância socioeconómica da viticultura nestas regiões, o acompanhamento do estado de hidratação das videiras é de suma importância. Embora a vinha seja uma cultura tipicamente de sequeiro, o stress hídrico pode resultar em perdas de produção quantitativas e qualitativas, e em danos irreversíveis nas plantas. A complexidade da resposta fisiológica das videiras à disponibilidade hídrica pode ser medida através de indicadores, que quantificam o grau de stress em que as plantas se encontram, e que permitem tomar decisões em conformidade. Assim, este trabalho descreve os principais indicadores de stress hídrico usados em viticultura, bem como as particularidades de cada um e a relação que existente entre eles, contribuindo para melhorar a sua compreensão.

Keywords: Water stress, stomatal conductance, water potential, vegetation indices, canopy temperature.
Palavras-chave: Stress hídrico, condutância estomática, potencial hídrico, índices vegetativos, temperatura da copa.

INTRODUCTION

Vines are found in a large number of regions around the world and have been linked to human history since ancient times, having always been of great economic importance (Chauvet and Reynier, 1984; Canas *et al.*, 2020). However, despite the geographic representation, most of the vineyards are located in regions where water is a limiting resource due to the uneven distribution of precipitation throughout the year. Regions with a temperate/Mediterranean climate, with rainfall concentrated in winter period and hot, dry summers, are examples of this (Cifre *et al.*, 2005; Chaves *et al.*, 2007; Baeza *et al.*, 2019).

Several climate forecasts point to southern Europe and the Mediterranean Basin becoming a "climate change hotspot" due to significant rise in temperature and increasingly irregular rainfall (Jones *et al.*, 2005; Schultz and Stoll, 2010; Fraga *et al.*, 2012, 2013; Van Leeuwen *et al.*, 2019; Dinis *et al.*, 2022).

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This scenario makes wine growing vulnerable in these regions and represents a major restriction on growth and development of vines, making it crucial to adopt strategies to adapt plants to these conditions (Malheiro *et al*., 2010; Fraga *et al*., 2012, 2013; Van Leeuwen *et al*., 2019; Sancho-Galán *et al*., 2023), since the post-flowering period coincides exactly with the period in which water scarcity is higher (Medrano *et al*., 2003; Flexas *et al*., 2010; Serra *et al*., 2014). Therefore, according to Simonneau *et al*. (2017), water scarcity associated with climate change is a particular threat to the sustainability of viticulture in current growing areas, which are generally prone to drought.

Unlike most crops, grapevines are generally very tolerant of water scarcity, being able to survive even under conditions of severe water stress, but such conditions can be detrimental to the fruit quality, due to a marked inhibition of the vegetative growth and a consequent reduction in photosynthetic capacity and, therefore, reduction in the plants' ability to properly ripen the grapes (Romero *et al*., 2010; Serra *et al*., 2014; Baeza *et al*., 2019; Pérez-Álvarez *et al*., 2021; Dinis *et al*., 2022). Berli and Bottini (2013), also found a reduction in shoot length and leaf area due to smaller leaf size and fewer leaves. Doupis *et al*. (2010), Li *et al*. (2010), and Pollastrini *et al*. (2011) observed a greater leaf thickness and specific leaf mass, and lower biomass, in response to increased temperature and solar radiation. In contrast, Fernandes de Oliveira and Nieddu (2016) found that the physiological responses of grapevines in the Mediterranean region depend on the intensity and duration of exposure to high temperatures and UV radiation.

Genetically, there are differences between vines in terms of their ability to tolerate levels of water restriction (Serra *et al*., 2014), which means that responses to environmental constraints vary from variety to variety (Costa *et al*., 2012; Tomás *et al*., 2012) due to physiological differences in the ability to regulate stomatal activity and water use (Chaves *et al*., 2007; Costa *et al*., 2012; Tomás *et al*., 2014).

Vines are classified as isohydric, if they start to close their stomata as soon as the water content in the soil decreases, or anisohydric if they do not close their stomata and continue to transpire even if the water reserves in the soil start to decrease (Schultz, 2003; Soar *et al*., 2006; Damiano *et al*., 2022). Thus, according to Flexas *et al*. (2010), Serra *et al*. (2014), Costa *et al*. (2016a) and MacMillan *et al*. (2021), the use of genotypes that are physiologically more sensitive to variations in the soil water content will contribute to greater success in adapting vines to climate change, as they have greater capacity to adjust the opening/closing of stomata according to the availability of water.

In this context, it is important for viticulture to monitor the water status of plants, which can be done through some physiological indicators, given the knowledge of the responses of vines to water scarcity. Stomatal conductance, water potential, canopy temperature and vegetative indices are widely used for this purpose (e.g. Vaz *et al*., 2016; Gutiérrez *et al*., 2017, 2018; Salgado-Pirata, 2018; Giovos *et al*., 2021; Mirás-Avalos and Araujo, 2021). According to Giovos *et al*. (2021), the normalized difference vegetation index (NDVI), is the most used vegetation index to assessment vineyard water status (Figure 1).

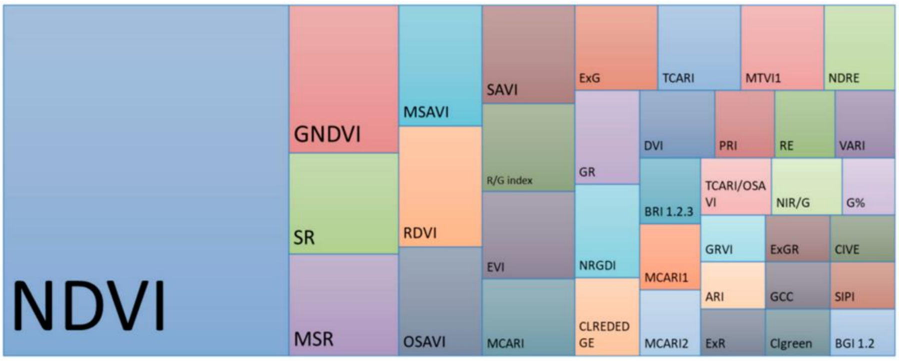

Figure 1. Remote sensing vegetation indices used in viticulture, represented with a proportional rectangle area. (NDVI – normalized difference vegetation index; GNDVI – green normalized difference vegetation index; SR – simple ratio; MSR – modified simple ratio; MSAVI – modified vegetation index adjusted for soil; RDVI – renormalized difference vegetation index; OSAVI – optimized soil-adjusted vegetation index; SAVI – soil-adjusted vegetation index; R/G index – red/green index; EVI – enhanced vegetation index; MCARI – modified chlorophyll absorption ratio index; ExG – excess green index; GR - green minus red index; NRGDI – normalized red-green difference index; CLREDEDGE – red edge chlorophyll index; TCARI – transformed chlorophyll absorption ratio index; DVI - difference vegetation index; BRI – blue-red pigment index; MTVI – multi-temporal vegetation index; PRI - photochemical reflectance index; TCARI/OSAVI - transformed chlorophyll absorption ratio index/optimized soil-adjusted vegetation index integrated form; GRVI – green-red vegetation index; ARI – anthocyanin reflectance index; ExR – excess red index; RE – red edge index; NIR/G – near infrared/green index; ExGR - excess green minus red index; GCC – green chromatic coordinate; Clgreen – green chlorophyll index; NDRE – normalized difference red edge; VARI – visible atmospherically resistant index; G% - vegetation greenness; CIVE – color index of vegetation extraction; SIPI – structural independent pigment index; BGI – blue-green pigment index). Source: Giovos *et al*. (2021).

STOMATAL CONDUCTANCE

The stomata closure and the consequent decrease in stomatal conductance (g_s) are the first processes that occur as a response in grapevines to water deficit (Serrano *et al*., 2010).

Stomata are pores that control the exchange of water vapor, carbon dioxide and oxygen between the plant and the atmosphere (Hetherington and Woodword, 2003), which is essential for the photosynthesis process, so closing the stomata can have serious consequences for the plant, because it inevitably leads to a decrease in photosynthesis (Simonneau *et al*., 2017).

The g_s regulation is highly conditioned by the synthesis and concentration of abscisic acid (ABA), produced in the roots during the soil water scarcity situations and transported in the xylem to the leaves, inducing the stomata closure (Cifre *et al*., 2005; Jiang and Hartung, 2008; Pou *et al*., 2008; Simonneau *et al*., 2017).

According to Cifre *et al*. (2005), the synthesis of ABA occurs at relatively high levels of water in the soil, which makes g_s a very precise tool in determining the water status of the plant. For this reason, ABA is considered one of the most important phytohormones in signaling soil water deficit (Davis *et al*., 2005; Schachtman and Goodger, 2008). ABA synthesis and stomatal regulation depend on the genotype (Prieto *et al*., 2010; Perrone *et al*., 2012), being higher in varieties with isohydric behavior and lower in those with anisohydric behavior (Soar *et al*., 2006). This is a critical factor in the adaptation of vines to drought, as Prieto *et al*. (2010) found. These researchers carried out a study in the south of France with five grapevine varieties, and observed that in hot and dry environments, extreme isohydric behavior drastically reduced the capacity to capture carbon, which is essential for photosynthesis, thus affecting the composition of the grapes and the yield (due to stomatal resistance). On the other hand, anisohydric behavior allows grapes to reach maturity in periods of drought, although it increases the probability of mortality due to hydraulic constraints (due to lower stomatal resistance).

However, there may be intrinsic variability in the use of water, as observed by Chaves *et al*. (2010) and Salgado-Pirata (2018) in the 'Aragonês' variety, whose iso- or anisohydric behaviour is unclear, since this variety experienced various types of behavior depending on the different tests it was subjected to. Similarly, Lovisolo *et al*. (2010), Pou *et al*. (2012) and Zhang *et al*. (2012) argued that a strictly iso- or anisohydric classification may be inappropriate, because the same varieties can behave differently depending on the particular combination of factors that condition it.

Medrano *et al*. (2002), Flexas *et al*. (2004) and Cifre *et al*. (2005) stated that, in general, for g_s above 150 mmol $H_2O/m^2/s$ photosynthetic limitations in vines are only of a stomatal quality; between 150 and 50 mmol $H_2O/m^2/s$ the impact on photosynthetic activity is at the limit of stomatal insufficiencies and the beginning of non-stomatal insufficiencies; and below 50 mmol $H_2O/m^2/s$ the vines are under severe water stress and photosynthetic limitations are already of a non-stomatal quality (Figure 2). Nevertheless, if there is some availability of water and according to the characteristics of each grape variety, the quantitative g_s results can be very sundry, as shown by Tomás *et al*. (2014).

Figure 2. Stomatal conductance measurement using a leaf porometer. Source: Salgado-Pirata (2018).

WATER POTENTIAL

The water potential (Ψw) quantifies the free energy of water and represents the water retention forces in the plant, or the tension force that has to occur in the plant in order for it to draw water from the soil (xylem negative hydrostatic pressure).

Ψw measuring through a pressure chamber, specifically for this purpose, is a very popular methodology for determining the plants hydration status (Martínez *et al*., 2013).

Conventionally, as explained by Simonneau *et al*. (2017), pure water (at sea level) has a potential equal to zero ($\Psi = 0$), corresponding to maximum water availability in a saturated soil.

Drying out the soil results in a decrease in its Ψw, which becomes more negative as the water binds to the soil particles and concentrates the solutes.

There are different types of approaches to assessing the plants water status using this methodology, since the leaf stem Ψw can be measured at midday, and also leaf Ψw can be measured at pre-dawn (Williams and Araujo, 2002; Williams and Trout, 2005; Van Leeuween *et al*., 2008, 2009; Cole and Pagay, 2015). Zsófi *et al*. (2009) argued that the pre-dawn Ψw determination is the most accurate indicator of the plants' water status compared to midday Ψw.

Indeed, pre-dawn Ψw better represents the hydration status of plants in relation to water availability in the soil, as it is measured at a time when, due to the absence of light (necessary for photosynthesis) and the low cooling requirements of the leaves, the stomata are closed and there is no loss of water through transpiration, which allows a balance to be established between the plant Ψw and the soil Ψw (Jones, 2007; Rodrigues *et al.* , 2012).

However, Améglio *et al.* (1999) warn that the determination of pre-dawn Ψw is inadequate when soils are very heterogeneous (variable soil water content), as the rehydration of plants during this period will depend on their location in areas with greater or lesser water retention capacity, and these results may be variable.

Van Leeuween *et al*. (2008) explained that the vines pre-dawn Ψw is in balance with the wettest layer of soil exploited by the root system, and thus a small layer of moist soil may be able to rehydrate the vine during the night, but may be insufficient to satisfy daytime evapotranspiration, especially when the canopy is large.

Without limiting factors (biotic or abiotic stress, or midday depression photosynthetic performance), midday corresponds to the moment when the plant reaches maximum photosynthetic capacity. Thus, Van Leeuween *et al*. (2008, 2009) considered the midday leaf Ψw, an indicator of the minimum Ψw (lowest hydration state) experienced by the plant during the day, as it coincides with the moment of maximum transpiration (and evaporation of soil water). In addition, according to Choné *et al*. (2001), the midday stem Ψw is a parameter capable of providing the first indication of the existence of water stress, being well correlated with leaf transpiration.

Matthews *et al.* (1987) and Williams and Trout (2005), stated that the midday leaf Ψw is a sensitive parameter in evaluating the plants water status, capable to distinguish the hydration status of grapevines subjected to different water regimes treatments.

However, according to Jones (2007), it does not always properly reflect the plants water status because the measurement represents the Ψw of just one leaf, while the stem Ψw represents the entire plant. Furthermore, the stem Ψw is less susceptible to temporal, environmental and individual leaf variations, compared to the leaf Ψw (Patakas *et al*., 2005; Shackel, 2007).

Ojeda (2007), Van Leeuwen *et al*. (2008), Martínez *et al*. (2013) and Mirás-Avalos and Araujo (2021), presented reference values for Ψw, relative to different stress levels, as shown in Table I.

CANOPY TEMPERATURE

Determining canopy temperature, through infrared thermography (Figure 3) or thermometry, allows monitoring the plants water status and stomatal behavior, which are dependent on transpiration (Van Zyl, 1986; Jones *et al*., 2002; Fuentes *et al*., 2012; Costa *et al*., 2012, 2013, 2016b; Bellvert *et al*., 2014; Pou *et al*., 2014; Grant *et al*., 2016). This relationship is based on the fact that when water is available, transpiration is higher and leaf temperature is lower, but when plants are under water stress, they close their stomata, transpiring less and have higher canopy temperatures compared to those in water comfort (Serrano *et al*., 2010; Fuentes *et al*., 2012; Pou *et al*., 2014, Costa *et al*., 2016b). It is important to monitor the vineyard canopy temperature because exposure to high temperatures, as occurs in the Mediterranean summer, is known to reduce photosynthesis in vines due to stomatal constraints (Soar *et al*., 2009; Yu *et al*., 2009; Zsófi *et al*., 2009).

Table I

Reference values for Ψw in relation to the vines water deficit degree

Water Stress Level	**$\Psi w_{\text{leaf pd}}$** (MPa)	**Ψw_{leaf}** (MPa)	**Ψw_{stem}** (MPa)
No stress	> -0.2	> -0.9	> -0.6
Mild	-0.2 to -0.3	0.9 to -1.1	-0.6 to -0.9
Mild to moderate	-0.3 to -0.5	-1.1 to -1.3	-0.9 to -1.1
Moderate to severe	-0.5 to -0.8	-1.3 to -1.6	-1.1 to -1.4
Severe	< -0.8	< -1.6	< -1.4

Ψw leaf pd – pre-dawn leaf water potential; Ψw leaf – midday leaf water potential; Ψw stem – midday stem water potential.

In a study carried out on potted 'Semillon' grapevine, Greer and Weston (2010) found a reduction in photosynthesis caused by the stomatal limitation activity after heat events (40 ºC). According to Costa *et al.* (2016b), very high air temperature conditions and low atmospheric humidity values, result in canopy temperatures several degrees above the air temperature, which makes it essential to determine the water status of the vines quickly and efficiently.

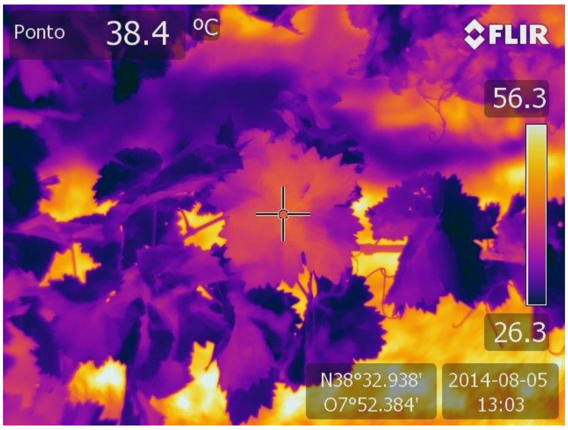

Figure 3. Canopy temperature measurement by infrared thermography. Source: Salgado-Pirata (2018).

In response to the importance of monitoring canopy temperature, the infrared thermography and thermometry, in addition to making it possible to monitor the temperature of the canopy of each vine, have the advantage of obtaining a high volume of data representative of the hydration status of plants at a higher level of spatial scale (Serrano *et al.*, 2010; Fuentes *et al.*, 2012). Therefore, they also allow monitoring the temperature distribution of the set of vines in the vineyard, bypassing the problems associated with determining other indicators which, because they are more localized, tend to show greater variability and require much more time to obtain a similar volume of information (Fuentes *et al.*, 2012).

VEGETATIVE INDICES

Multispectral sensors have been identified as a tool of interest in studies related to the status of plants because they have the ability to predict certain spectral indices. These sensors are installed on space-based (satellites), aerial (aircraft) or ground-based (portable devices) platforms (Govender et al., 2009; Huang et al., 2016), and are mathematical combinations of reflectances (two or more) at specific wavelengths.

The Normalized Difference Vegetation Index (NDVI) is a widely used technique for studying the biophysical characteristics of vegetation (e.g. Jiang *et al.*, 2006; Salgado-Pirata, 2018; Giovos *et al.*, 2021), calculated using the Equation 1.

$$\text{NDVI} = (\text{NIR} - \text{R}) / (\text{NIR} + \text{R}) \qquad \textbf{Eq.1}$$

proposed by Rouse *et al.* (1973), where NIR and R correspond to the wavelengths reflected by vegetation and quantified by a sensor, appropriate for this purpose, in the near infrared (0.76 – 0.90 µm) and red (0.63 – 0.69 µm) regions, respectively. Terrón *et al.* (2015) elucidated that when electromagnetic radiation falls on leaves (vivid green), part of it is absorbed, another part is transmitted and the remaining part is reflected. The spectral range of electromagnetic radiation that can be absorbed by plants is photosynthetically active radiation. Within this range, chlorophyll assimilates the red and blue bands, and reflects the green, infrared and near-infrared bands. Thus, based on the NDVI, the greater amount of vegetation cover or canopy, the higher the value of this index. Terrón *et al.* (2015) also warn that the ability of the vines to absorb and reflect radiation is limited by the degree of stress they are under. As such, a vine that is under water stress or any other type of stress (pests, diseases, nutritional deficiencies), will have less capacity to absorb in the red band and reflect in the near infrared band through the cell walls, and consequently will have a lower NDVI. This is partly due to the degradation of carotenoids, which aid in the absorption of light in regions of the visible range (0.4 – 0.7 µm) where chlorophyll does not absorb so efficiently, and which allow the detection of changes in the environmental conditions of the vineyards (Dhami and Cazzonelli, 2020).

Several authors (Broge and Leblanc, 2001; Dobrowski *et al.*, 2002; Johnson, 2003; Johnson *et al.*, 2003; Gitelson, 2004; Hall *et al.*, 2008; Giovos *et al.*, 2021) reported that NDVI is broadly related to the production of biomass and vegetative vigor of grapevines, which means that any change in the factors affecting the vegetative expression of these plants can be estimated through this technique.

WATER STATUS INDICATORS PARTICULARITIES AND RELATIONSHIPS

Comstock (2002) mentioned disadvantages associated with Ψw for plant water status determination. The author stated that it weakly correlates with soil water deficit, while stomatal closure is well correlated with soil water deficit due to the efficiency of chemical signaling (ABA) in the vines. Something that was also verified by Salgado-Pirata (2018), who found that g_s is more sensitive to the hydration state variations of vines than Ψw. In this sense, Rodrigues *et al.* (2012) pointed out that the Ψw values for plants with a high transpiration rate can be similar to the Ψw values of plants that suffer water stress, since:

i) when there is a lot of water in the soil and the plants can extract it easily, there are high rates of transpiration that induce a drop in water pressure in the leaves and, consequently, a decrease in Ψw (more negative); and ii) when soil water reserves are scarce, plants close their stomata to prevent water loss that would be difficult to recover, and, therefore, Ψw becomes less negative. These phenomena may influence the correct estimation of plant water status.

Similarly, in potted plants, Serrano *et al.* (2010) found that differences in water supply caused differences in net photosynthetic carbon assimilation, g_s and water index, despite similar pre-dawn Ψw.

Möller *et al.* (2007), Baluja *et al.* (2012), Costa *et al.* (2012), Pou *et al.* (2014) and Gutiérrez *et al.* (2017, 2018) found the existence of relatively strong correlations between g_s and Ψw, and vine canopy temperature or thermal indices.

In contrast, Salgado-Pirata (2018) found only weak to moderate correlations ($0.16 \leq R^2 \leq 0.48$) between g_s and the crop water stress index (CWSI), noting that a higher CWSI is not always, which would initially indicate greater water stress, was reflected in lower g_s and vice versa. However, the year in which this test took place (2014) represented less severe water stress for the vines. It was also verified by Costa *et al.* (2016b), who found stronger and more significant correlations between canopy temperature and g_s or pre-dawn Ψw in years of higher stress; that is, these authors found that there was inter-annual variability in the correlations obtained, which was caused by the variability of climatic conditions. Specifically, they noticed that in 2013 the water stress in the vines was greater than in 2014, and generated stronger and more significant correlations than those observed in 2014.

Similar results were found by Pagay and Kidman (2019) that observed the relationship between conventional vine water status measures and CWSI seemed stronger in the warmer and drier season than in the cooler and wetter season. Sepúlveda-Reyes *et al.* (2016), also mention that the best relationships between CWSI and plant-based variables were registed during the period of maximum atmospheric demand.

The g_s, Ψw and canopy temperature reflect a response to the plants' hydration status in the short term, while NDVI reflects a long-term response (Baluja *et al.*, 2012). In this way Salgado-Pirata (2018) found that NDVI in the summer period is well correlated with the accumulated precipitation from January to May, providing that the vines vegetative growth is strongly conditioned by the accumulated precipitation during the first months of the year; that is, in the experimental conditions of this study (Temperate/Mediterranean climate), the higher the accumulated precipitation from January to May, the higher the average NDVI value. To countering these results, the author also analyzed the NDVI in the summer period and the accumulated precipitation from October to December of the previous year; it was found that this did not have as much influence on the vegetation dynamics as the accumulated precipitation from January to May of the same year. Similarly, the accumulated precipitation from June to September plus irrigation have little influence, which is perfectly understandable, since between June and September, in Mediterranean conditions, rainfall is scarce and the water supplied through irrigation is not enough to change vegetative patterns, but only to maintain the physiological activity of plants.

Several authors (Montero *et al.*, 1999; Johnson *et al.*, 2001, 2003; Johnson, 2003; Hall *et al.*, 2002, 2003; Stamatiadis *et al.*, 2010; Taylor and Bates, 2013) stated that the NDVI determination is a methodology: i) that allows growers to identify issues in specific areas of the field; ii) has the potential to be a tool to support technical vineyard management decisions; iii) it can be used to estimate differences in the grapes quality (Hall *et al.*, 2003) and to design selective harvesting strategies (Bramley *et al.*, 2011); iv) allowing information to be obtained on a large scale (Santesteban *et al.*, 2013) and almost in real time (Huang *et al.*, 2016).

However, it has some drawbacks, as sensors vary widely in their discrimination capacity. Sensors carried by aircraft or satellites are normally more limited by spatial resolution, but also by the effect, individually or combined, of factors such as meteorological conditions, revisit time, interference of the shadow cast on the ground by plant architecture and vegetation heterogeneity (Jiang *et al.*, 2006; Govender *et al.*, 2009; Marques da Silva *et al.*, 2015). Thus, ground-based sensors, whose resolution capacity varies according to the height in which the device is placed in relation to the vegetation (spectral reflectance measurements at the canopy and/or leaf scale), constitute an emerging technology that allows overcoming the issues associated with aerial and space-based sensors, which, because they further away, are limited to distinguishing what is vegetation from what is not vegetation (Reyniers *et al.*, 2006).

Huang *et al.* (2016) also ascribed advantages to ground-based sensors in terms of flexibility, portability and control of procedures, compared to the use of space or airborne sensors.

However, ground-based multispectral sensors can be active, if they use their own light source, or passive, if they do not have their own light source and normally use sunlight. According to Stamatiadis *et al.* (2010), passive sensors need to be calibrated frequently in order to overcome the issues related to clouds, light intensity and the projection of shadows from vines, while active sensors do not require frequent calibration and work well in all lighting situations, even at night.

These authors also found that passive sensors are more sensitive to the NDVI saturation effect, which resulting in the inability to distinguish differences in the vegetative characteristics of vines under high growth conditions, compared to active sensors, which do not tend towards saturation in conditions of high vegetation.

The advantage of using vegetative and thermal indices, compared to g_s and Ψw, is related to the fact that the firsts two allow measurements on a higher scale, and as such are more representative of the whole, compared to localized measurements of g_s and Ψw.

In this regard, Espinoza *et al*. (2017) highlighted significant correlations between NDVI and canopy temperature, and leaf g_s. These researchers claimed that this study demonstrated the potential of using low-altitude multispectral and thermal imaging data in the assessment of relative degree of plant water stress. In addition, they stated that thermal infrared images can be used as a rapid tool to estimate leaf stomatal conductance, indicative of the spatial variation in the vineyard. This is critically important, as this data will provide a near real-time assessment of crop stress.

Similar theory was outlined by Diago *et al.* (2022), who found the satisfactory performance of the multivariate models involving thermal, environmental and spectral data to either estimate or classify the plant water status within a vineyard. The researchers support the approach towards the combination of different data source to improve the capabilities of each one.

Tosin *et al*. (2020) estimated the grapevine pre-dawn leaf Ψw based on hyperspectral reflectance data in Douro wine region. According to the authors, the accuracy and operability of this predictive model provide a good perspective for its use in monitoring grapevine water status and supporting the irrigation tasks.

CONCLUDING REMARKS

The environment is increasingly conditioning wine-rowing activities due to the instability of water availability. In plants, water deficit is a major constraint on the main metabolic functions, gas exchange and photosynthesis. Water management is therefore essential to ensure the growth and development of plants and to produce crops economically, resulting in consistent and quality harvests.

Through a set of references on a relatively broad time scale, this work revealed which are the main indicators of water stress used in viticulture and the relationships between them, with very particular nuances regarding each one. So, their use on an individual basis must consider these aspects, and, in an ideal scenario, the use of these indicators would be managed in a complementary way.

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