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SHORT COMMUNICATION

Observation of shoot growth: a simple and operational decision-making tool for monitoring vine water status in the vineyard

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ABSTRACT

In vineyard management, the monitoring of vine water status is of great importance, because this variable influences harvest quality, yield and, in the longer term, vineyard sustainability. Numerous tools and methods have been proposed to monitor vine water status, but they often involve the use of costly and complex equipment and can be logistically demanding. Methods based on the observation of vine shoot growth are interesting potential alternatives, because they are simple to carry out and therefore potentially better adapted for use in production vineyards. However, these methods have never been evaluated or compared to reference measurements made on several cultivars and during several vintages. The objective of this article was to study their characteristics (validity range, specificity and sensitivity) in order to be able to give recommendations for their rigorous implementation in an experimental or operational context. The study was carried out using the iG-Apex method to measure vine shoot growth and predawn leaf water potential as reference measurements in 55 fields located in the Tavel vineyard (Occitanie, France) during the 2008 to 2012 vintages. The results showed that iG-Apex can be used as an operational tool for monitoring vine water status at field scale and for a predawn leaf water potential ranging from -0.2 MPa to -0.8 MPa. Nevertheless, precautions must be taken when interpreting the results, as the method is not specific to water constraint and is also sensitive to other phenomena. Furthermore, it could be relevant to use this method for the collective monitoring of vine shoot growth over large spatial areas, in addition to more precise and more localised monitoring carried out with reference measurements.

KEYWORDS: apex, grapevine, vegetative indicator, *vitis vinifera*, water potential, water restriction, water stress

INTRODUCTION

Many authors have shown that water constraint decreases photosynthesis and transpiration (Hsiao, 1973), thus limiting vegetative growth (Lebon *et al*., 2006) and influencing berry ripening (van Leeuwen and Seguin, 1994). In the vineyard, water stress has been shown to limit yield (Ojeda *et al*., 2001), influence grape quality (van Leeuwen *et al*., 2009) and impact the following year's production (Guilpart *et al*., 2014). Measuring and monitoring water status is therefore of major importance in vineyard management. Many tools and methods have been proposed for estimating vine water status (Rienth and Scholasch, 2019). They all rely on the measurement of a variable that varies with or explains water status and that can either be measured on the soil (Gardner *et al*., 2001) or the plant (Pons *et al*., 2008) or derived from climate parameters (Gaudin *et al*., 2014). Most of these approaches have been designed to meet the requirements of research and experimentation aiming to obtain the most reliable proxy of the plant's water status. As a result, they often require the use of expensive equipment and the implementation of complex protocols. These operational constraints limit the use of these tools at a large scale in the vineyard. The Predawn Leaf Water Potential (ψ_{PD}) may be a good example of this: it is considered as a reference method (Carbonneau, 1998), but it remains relatively little used in commercial vineyards, because it involves carrying heavy and voluminous equipment and making measurements under restrictive conditions with qualified operators.

Methods based on shoot growth observations could be interesting alternatives for estimating vine water status (Pellegrino *et al*., 2005). They are simple to implement and therefore potentially more suitable for use in commercial situations. Schultz and Matthews (1988) have shown that shoot extension rate is more rapidly affected by water stress than leaf extension rate. As a result, comparing these two extension rates by simply folding the last unfolded leaves on the shoot is a relevant indicator for estimating how water constraint affects shoot growth. Based on this principle, Rodriguez Lovelle *et al*. (2009) produced a protocol for observing 50 shoots spread over 10 vines. Martinez-De-Toda *et al*. (2010) proposed the use of an operational indicator based on the observation of these shoots' apexes and their classification into three categories: i) apex in full growth (FG) when organogenesis is active, ii) apex in moderate growth (MG) when organogenesis is reduced, and iii) apexes with stopped growth (SG) when the apex has fallen or has dried out. These authors summarised these observations using the indicator *S*.

$$S = w_{FG}S_{FG} + w_{MG}S_{MG} + w_{SG}S_{SG}$$

where W_{FG}, W_{MG}, W_{SG} stand for the proportions of full growth, moderate growth and stopped growth apexes respectively. S_{FG}, S_{MG}, S_{SG} are the coefficients associated with each type of apex (Equation 1). In this paper, the values 1, 0.5 and 0 were considered for the parameters S_{FG}, S_{MG}, S_{SG} respectively and the *S* indicator is therefore referred to as the iG-Apex indicator (Equation 2).

$$\text{iG-Apex} = S_{FG} + 0.5S_{MG}$$

Despite the simplicity of this approach, the few studies on its potential usefulness for decision support are limited to a single grape variety and two vintages (Martinez-De-Toda *et al*., 2010). However, it has been shown that vine shoot growth can be influenced by numerous factors, such as genetics (Prieto *et al*., 2010), nitrogen access (Gaudillère *et al*., 2002), farming practices (Meissner *et al*., 2019) and fruit load (Hardie and Martin, 2000). As a result, the potential and limitations of the iG-Apex method for monitoring vine water status in commercial situations have not been properly explored. The objective of this paper is therefore to study the characteristics of iG-Apex measurements in order to propose recommendations for a rigorous implementation of this method in an operational context. First, the iG-Apex sensitivity (the ability of iG-Apex measurements to vary with water status), range of validity (water status values for which iG-Apex measurements vary with water status) and specificity (the ability of iG-Apex measurements to vary only with water status) are investigated. Second, the iG-Apex repeatability (similarity of several iG-Apex measurements performed under the same conditions) and reproducibility (here, similarity of several iG-Apex measurements performed by different operators under similar conditions) are evaluated.

MATERIALS AND METHODS

1. The general approach

First, iG-Apex measurements were compared to measurements made with a reference method for monitoring the vine water status; i.e., Predawn Leaf Water Potential. This comparison was performed using data collected in commercial situations from several fields, varieties and vintages. The corresponding dataset is henceforth referred to as vineyard_dataset. Second, the iG-Apex repeatability (similarity of several iG-Apex measurements performed under the same conditions) and reproducibility (here, similarity of several iG-Apex measurements performed by different operators under similar conditions) were evaluated. This study was conducted on data corresponding to repeated measurements by several operators. This dataset is henceforth referred to as metrological_dataset.

2. The vineyard_dataset

2.1. Sampling design

Measurements (shoot growth and reference) were collected in the vineyard of Tavel, in the southern Rhône Valley, France (WGS84; X= 4.682064; Y= 44.009484). The climate in this region is Mediterranean with low annual rainfall and high summer temperatures. The types of soils are relatively diverse, but the main factor limiting vine shoot growth is access to water resources (Martinez-Vergara *et al*., 2014).

55 measurement sites corresponding to 55 different fields were defined within the vineyard (Figure 1). The fields were

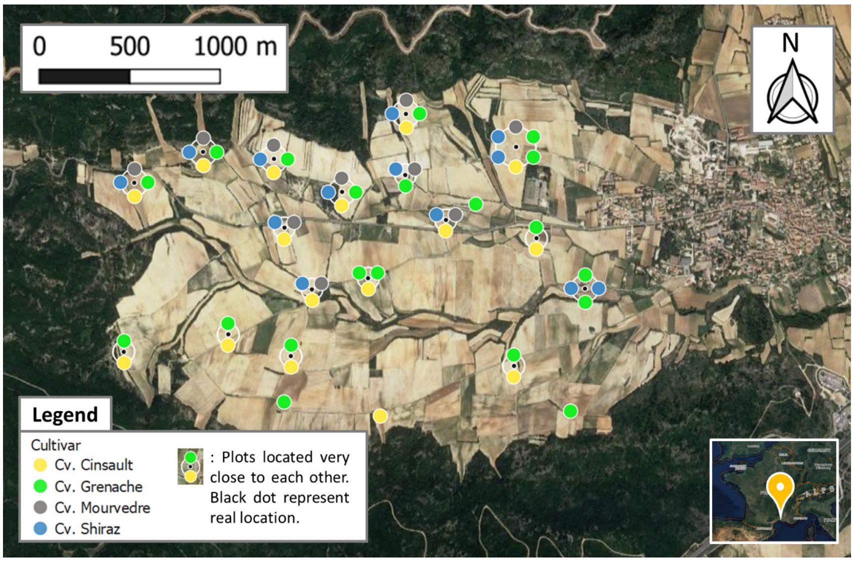

FIGURE 1. Location and cultivar of the fields from which reference and shoot growth measurements were collected for the Vineyard_dataset.

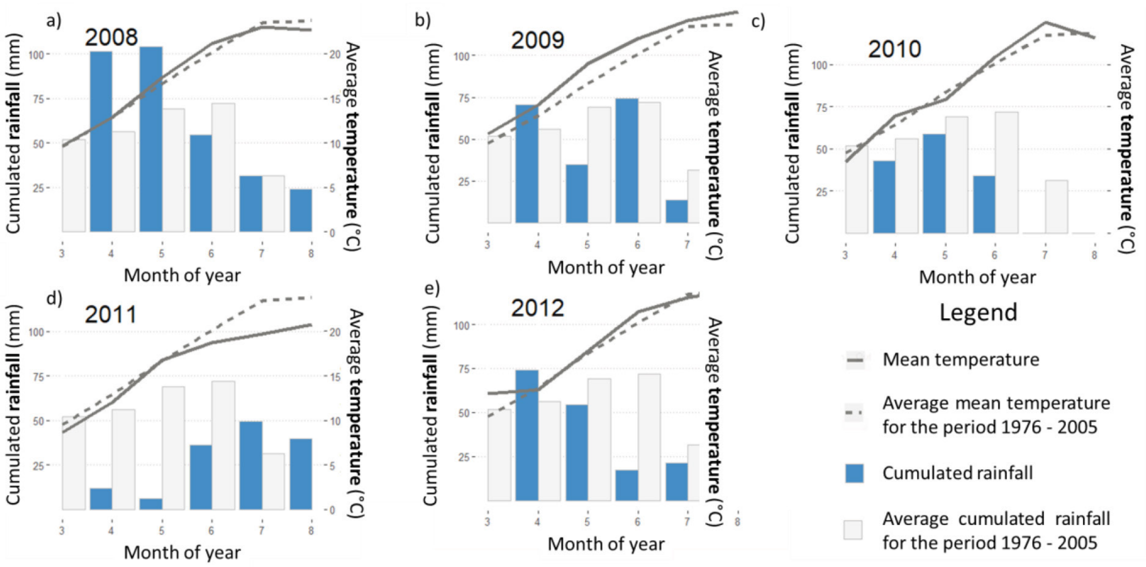

FIGURE 2. Average monthly temperatures and cumulative monthly rainfall for the (a) 2008, (b) 2009, (c) 2010, (d) 2011, and (e) 2012 vintages compared to the respective averages over the period 1976 – 2005.

situated in the same soil unit. The soil was sandy-clay with a considerable amount of calcareous stones on the surface. Each measurement site consisted of 10 consecutive vines along the row within each field. The fields were chosen in order to i) take into account the diversity of cultivars in the region (cv. Cinsault, cv. Grenache, cv. Mourvèdre and cv. Syrah), and ii) to cover a wide variety of situations in the study zone (Figure 1). The study was conducted over 5 consecutive years from 2008 to 2012. These vintages had a variety of temperature and rainfall profiles that allowed a wide range of climatic conditions to be explored (Figure 2); for example, 2008 was characterised by an exceptionally wet spring and early summer, while, in contrast, the early summer of 2011 was particularly dry. The year 2009 was warm compared to the temperatures observed over the last 30 years, but with average rainfall. In contrast, 2010 summer was dry with no precipitation.

At each site, measurements (shoot growth and reference) were collected on a weekly basis. Measurements were all collected between 30 May and 1 September, but each year the date of the first measurement was dependent on the weather and the resulting precocity or delay of water stress. At the end of the protocol, the *Vineyard_dataset* consisted of 474 pairs of shoot growth and reference measurements.

2.2. Collection protocol for iG-Apex measurements

For each of the 55 10-vine sites, 50 apexes were observed and classified as FG, MG and SG (Figure 3) for the calculation of the iG-Apex indicator (Equation 2).

FIGURE 3. Examples of shoot classified as (a) "full growth", (b) "moderate growth" and (c), "stopped growth".

2.3. Collection protocol for Predawn Leaf Water Potential measurements

The Predawn Leaf Water Potential (ψ_{PD}) was measured using a pressure chamber following the method given by Deloire *et al*. (2020). For each of the 55 10-vine sites, measurements were taken on the five central vines (vines 4 to 8). On each vine, measurements were made on a primary leaf located in the middle zone of the vegetation. The average of these 5 measurements was considered as the reference value for the site. The measurements were performed according to the method described by Améglio *et al*. (1999) by experienced operators who regularly calibrated each other to limit operator effects.

3. The Metrological_dataset

The iG-Apex measurements were made in conditions that allowed the widest possible range of shoot growth to be observed on the same date. These measurements were made in 3 fields planted with 3 cultivars of varying vigour and precocity (cv. Chenin, cv. Mourvèdre and cv. Syrah). These fields were located in Montpellier (WGS84; Lat: 43.617592; Long: 3.855987) in a Mediterranean climate. Each field consisted of a site of 10 consecutive vines along the row. Measurements were collected on 25 July 2019 when water stress was likely to impact shoot growth. Six inexperienced operators repeated the iG-Apex measurements three times at each of the three sites at 30-minute intervals. At the end of the procedure, the *Metrological_dataset* comprised 54 iG-Apex measurements (3 fields * 3 repetitions/fields * 6 operators). The measurements were made following the protocol described in Section 2.2.

4. Methods used to study the characteristics of the iG-Apex indicator

4.1. iG-Apex sensitivity

The objective was to study the strength of the relationship between iG-Apex and ψ_{PD} on the basis of Vineyard_dataset. To identify the major trend in this relationship, the average of values was plotted for every 0.1 iG-Apex interval. A linear regression was performed between iG-Apex and the corresponding average ψ_{PD}. The corresponding r-squared was calculated to evaluate the strength of the established relationship.

4.2. Validity range of iG-Apex

The objective was to identify the range of vine water status in which the relationship between iG-Apex and the ψ_{PD} was relevant. Only the extreme ranges of iG-Apex values in the *Vineyard_dataset* were taken into account in order to identify the situations where this indicator appeared to be saturated or not sensitive to ψ_{PD}; these were then plotted and studied in a two-dimensional graph ψ_{PD} vs iG-Apex. Linear regressions were performed and the corresponding r-squared was calculated to characterise the strength and therefore relevance of the relationship between iG-Apex and ψ_{PD} in both extreme cases.

4.3. Specificity of iG-Apex to vine water status

The objective was to i) check that iG-Apex measurements were a relevant proxy of vine water status, and ii) investigate whether the iG-Apex indicator was sensitive to other factors, such as variety or field effect, encompassing environmental factors and cultural practices. To do so, the standard deviation of values for each 0.1 iG-Apex interval was first studied as a proxy of the uncertainty in the relationship between iG-Apex and ψ_{PD}. Then, the sensitivity of iG-Apex to different factors was investigated using ANOVA and 3 variables: vine water stress, variety and field. The vine water stress was characterised based on the clustering of the ψ_{PD} values within four classes (ψ_{PD} > -0.2MPa; -0.2MPa > ψ_{PD} > -0.4MPa; -0.4MPa > ψ_{PD} > -0.6MPa; -0.6MPa > ψ_{PD}), corresponding to a mild or absent, mild to moderate, moderate to severe and severe water stress respectively (Deloire *et al*., 2004). It is worth noting that these thresholds can vary marginally depending on the characteristics of the soil, cultivar or rootstock (Charrier *et al*., 2018), but they were considered relevant for the purpose of this study. The magnitude of the effects of the three variables were compared in order to assess whether the sensitivity of the iG-Apex indicator to variables other than water status could be neglected or not. The influence of cultivar was further investigated by studying the standard deviation of the ψ_{PD} values in each class of iG-Apex for two cultivars, cv. Cinsault and Grenache. Both studies were performed on Vineyard_dataset.

4.4. Repeatability and reproducibility of iG-Apex

The objective was to investigate whether the iG-Apex measurements showed a repetition effect (was there an

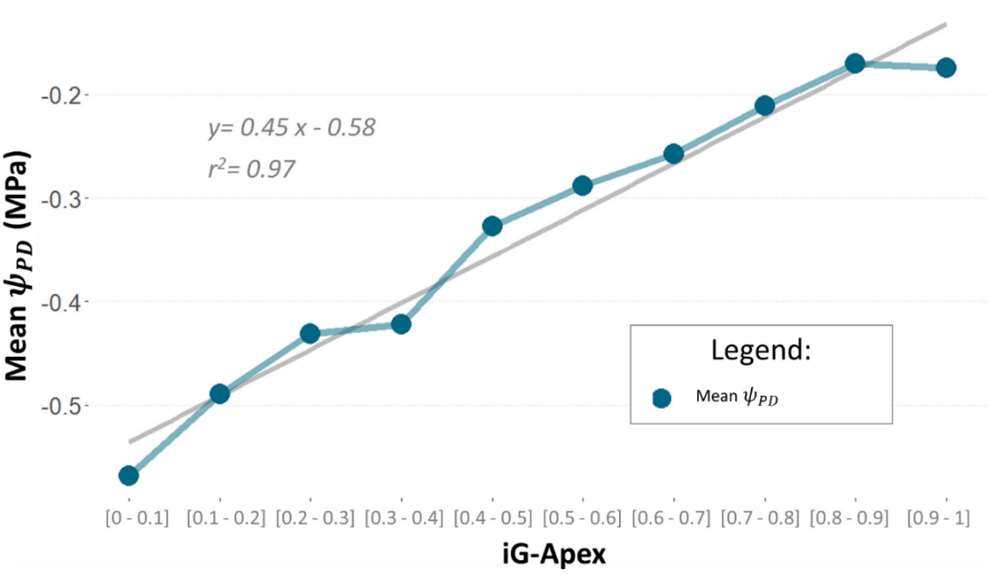

FIGURE 4. Mean of Predawn Leaf Water Potential ψ_{PD} depending on iG-Apex values for the 474 measurements of Vineyard_dataset.

effect when the same operator repeated a measurement?) and operator effect (was there an effect when different operators made the same measurement?). It was done using ANOVA with two variables: operator and repetition. This study was performed on the Metrological_dataset.

5. Graphs

All analyses and graphs were performed with R 3.6.1 (R Core Team, 2021).

RESULTS

1. iG-Apex sensitivity:

The results obtained with the 474 measurements of the Vineyard_dataset highlight a clear linear relationship ($r^2 = 0.97$) between classes of iG-Apex and mean ψ_{PD} observed for each considered class (Figure 4). The lower the iG-Apex, the lower the average ψ_{PD}. Low iG-Apex values correspond on average to vines experiencing water stress. This result clearly shows that iG-Apex is related to vine water status and that it can be used as a relevant surrogate in commercial situations. However, for extreme class of iG-Apex (iG-Apex < 0.1 and iG-Apex > 0.9), the general trend highlighted by Figure 4 is less straightforward; for example, for iG-Apex class > 0.9, a plateau is clearly observed, showing that mean ψ_{PD} for this iG-Apex class is not that different from mean ψ_{PD} observed for the next class (iG-Apex = [0.8; 0.9]).

2. Validity range of iG-Apex

When the results showed high shoot growth (iG-Apex > 0.9), ψ_{PD} varies over the whole range from -0.3 MPa to 0 MPa (Figure 5b). In this range, the linear model (ψ_{PD} vs iG-Apex) explains only a very small part of the variability ($r^2 = 6.8 \times 10^{-3}$). This result shows that shoot growth is not impacted by differences in water constraint when the latter is very low. Under these conditions, all apexes were in full growth and iG-Apex values remained very close to 1. The upper threshold of validity for the relationship between ψ_{PD} and iG-Apex is close to -0.2 MPa. These results are consistent with the scientific literature, in which $\psi_{PD} > -0.2$ MPa is shown to correspond to situations where water does not limit vine physiological functions (Deloire *et al*., 2004).

Regarding high water constraint ($\psi_{PD} < -0.8$MPa), almost all the results show very low shoot growth with iG-Apex of zero or very close to 0 (Figure 5a). Again, in this case, the linear model (ψ_{PD} vs iG-Apex) only explains a very small part of the variability ($r^2 = 1.6 \times 10^{-2}$). This result shows that beyond a given water constraint threshold (around -0.8 MPa), apex shoot growth stops. When the vine water status continued to decrease, the apexes remained in the same state and the iG-Apex indicator was therefore no longer sensitive to variations in vine water status. This result is consistent with the work carried out on potted vines by Schultz and Matthews (1988), who demonstrated that leaf and internode growth is very low when ψ_{PD} is around -0.8 MPa and it stops when ψ_{PD} is lower than -1 MPa.

For vine water status monitoring purposes, the validity range of iG-Apex to be considered is therefore between approximately -0.8 MPa and -0.2 MPa. Outside this range, observations of shoot growth cannot be used as a surrogate for estimating vine water status.

3. Specificity of iG-Apex to vine water status

The standard deviation of ψ_{PD} values is relatively low (around 0.06 MPa) for high iG-Apex (Figure 6) indicating, in these conditions, the specificity of iG-Apex to vine water status. The standard deviation is higher (around 0.20 MPa) for low iG-Apex. In other words, the lower the iG-Apex, the higher the uncertainty of the relationship between ψ_{PD} and iG-Apex. This result shows that, in our conditions, vine

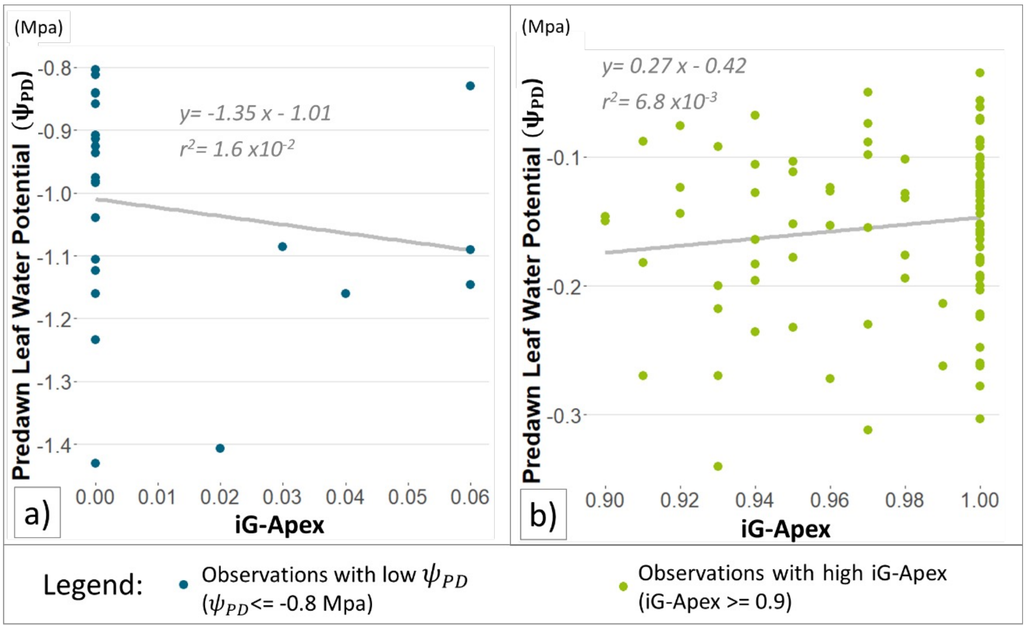

FIGURE 5. Scatter plots of Predawn Leaf Water Potential ψ_{PD} vs iG-Apex for: (a) measurements with high water constraint (ψ_{PD} < -0.8), and (b) measurements with active shoot growth (iG-Apex > 0.9).

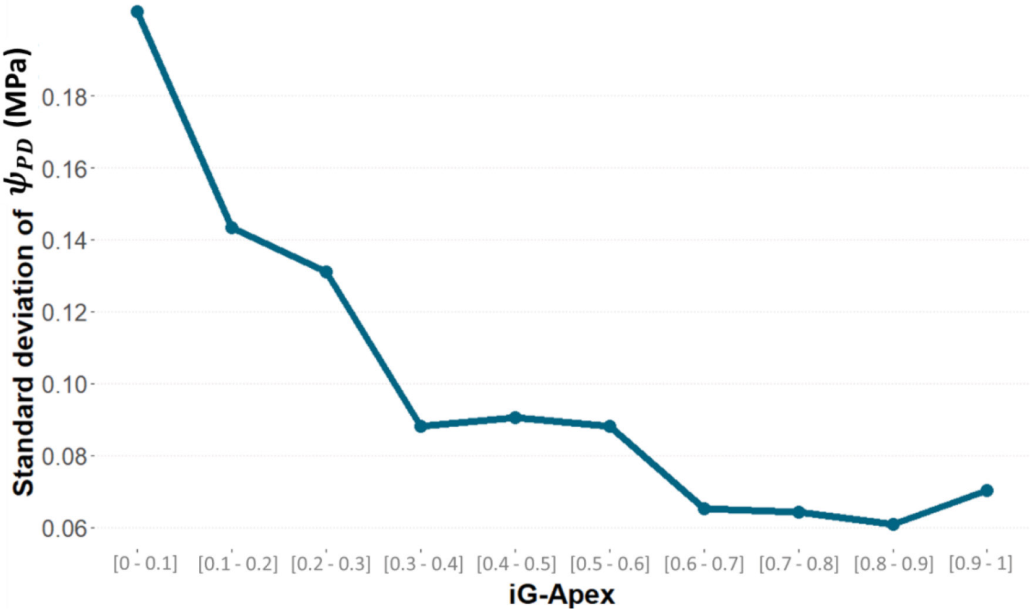

FIGURE 6. Standard deviation of Predawn Leaf Water Potential ψ_{PD} depending on iG-Apex values for the 474 measurements of Vineyard_dataset.

water status may not be the only factor affecting changes in iG-Apex; for example, a low iG-Apex value may correspond to a high water constraint, as well as to moderate water constraint, when another factor limits shoot growth (e.g., access to nitrogen). For low values, iG-Apex may therefore be less specific to vine water status and influenced by other factors.

The results of the ANOVA were used to determine the relative influence of these other factors compared to vine water status.

As expected, the class of is the main factor that explains the variability of iG-Apex, explaining 96.4 % (Mean square = 1.27*10^{1}) of its variability. This result is in accordance with the relationship shown in Figure 4. Compared to similar measurements made either in controlled conditions (Pellegrino *et al*., 2005) or in a small number of fields (Martinez-De-Toda *et al*., 2010), this result confirms the relevance of iG-Apex in a large diversity of fields when monitoring vine water status in commercial conditions. The field effect on iG-Apex values - encompassing both environmental factors and cultural practices - is less significant (p-value < 0.01), explaining only 0.005 % of variability (Mean square = 6.48*10^{-2}). In this experiment, the field effect includes all factors related to vineyard

TABLE 1. Results of the ANOVA performed on 474 iG-Apex measurements of Vineyard_dataset with three factors (cultivar, classes of ψ_{PD} and field).

	Degrees of freedom	Sum of Squares	Mean Squares	F-value	Probability	
Class of ψ_{PD}	3	$3.82*10^{1}$	$1.27*10^{1}$	$3.22*10^{2}$	$< 2*10^{-16}$	***
Cultivar	3	1.11	$3.71*10^{-1}$	9.39	$5.16*10^{-6}$	***
Field	54	3.50	$6.48*10^{-2}$	1.64	$4.36*10^{-3}$	**
Residuals	414	$1.63*10^{1}$	$3.93*10^{-2}$			

management (fertilisation, weed control, training system and pruning, etc.) that are likely to affect iG-Apex. Two hypotheses can be formulated regarding this relatively low field effect: either it is very low compared to the vine water status effect, or vineyard management is similar in the zone under consideration.

The cultivar variable had a significant effect (p-value < 0.001), although the proportion of variability explained by this factor was only 2.8 % (Mean square = $3.71*10^{-1}$). This cultivar effect is illustrated by plotting average ψ_{PD} versus iG-Apex for the two cultivars: cv. Cinsault and cv. Grenache (Figure 7). For the same class of iG-Apex, the standard deviation of ψ_{PD} was lower when only one cultivar was considered than when considering all cultivars (Figure 6). This result is consistent with the conclusions of Prieto *et al*. (2010). Although the cultivar effect on iG-Apex variability is small compared to the water stress effect, this result shows that taking into account the cultivar can improve the accuracy of the estimation especially for moderate to high water constraint levels (< -0.5 MPa). These results highlight the potential of variety specific models for improving the accuracy of ψ_{PD} estimations from iG-Apex, especially for moderate water constraint (ψ_{PD} < ~-0.4 MPa). However, the results of the present experiment do not allow us to conclude whether a specific model would be necessary for each cultivar or whether models for a few groups of cultivars with similar behaviour would be sufficient within a commercial context.

4. Repeatability and reproducibility of iG-Apex

The ANOVA (Table 2) shows that neither the operator nor the repetitions by the same operator have a significant effect on the iG-Apex values; the method is therefore repeatable and reproducible. It should be noted that this experiment was purposely conducted using non-expert users. Under these conditions, the results reinforce the repeatability and the reproducibility of the method.

5. Considerations for using iG-Apex to estimate vine water constraint in a commercial context

The observed sensitivity and specificity indicate that iG-Apex is a relevant indicator for the operational monitoring of vine water status. The range of validity shows that the iG-Apex method can be used for low to moderate water constraint (from -0.3 MPa to -0.8 MPa). These thresholds may be considered as orders of magnitude and they may be subject

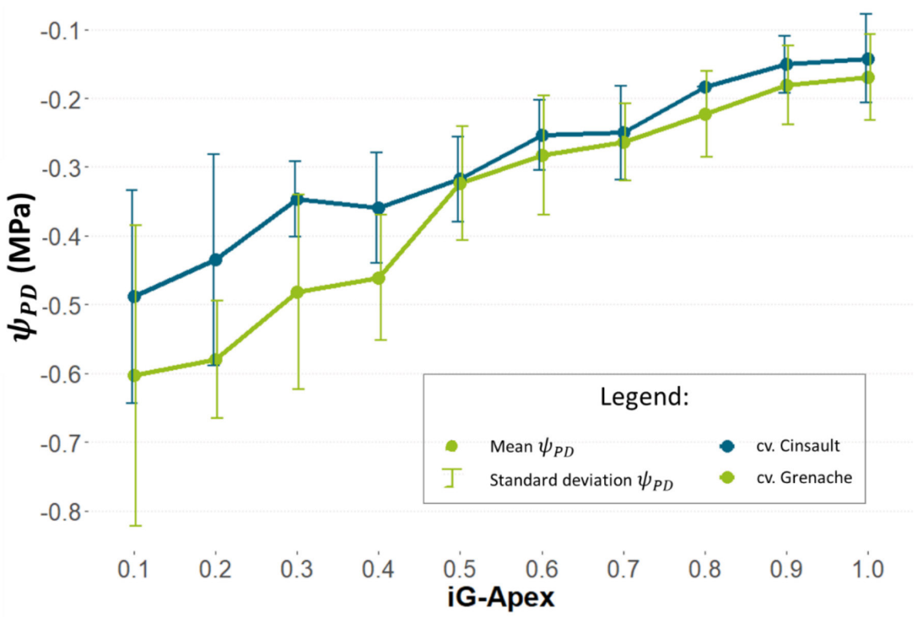

FIGURE 7. Mean and standard deviation of Predawn Leaf Water Potential ψ_{PD} depending on iG-Apex values for the 236 measurements made on cv. Cinsault and cv Grenache out of the 474 measurements of Vineyard_dataset.

TABLE 2. Results of the ANOVA performed on 54 iG-Apex measurements with two factors (operator and repetition).

	Degrees of freedom	Sum of Squares	Mean Squares	F-value	Probability
Operator	5	0.1732	0.03464	1.215	0.317
Repetition	2	0.0030	0.00151	0.053	0.948
Residuals	46	1.3113	0.02851		

to some variations depending on parameters such as soil type, cultivar or rootstock. Given that it is relatively simple to implement the iG-Apex method in commercial situations. It can be used for the dynamic monitoring of vine water status at the field level for these ranges of water constraint. Its good repeatability and reproducibility are important, because the monitoring of vine water status within different fields by different operators are still relevant for making comparisons. Comparing the dynamics of two fields with different cultivars will also be possible since the cultivar effect is smaller than the water stress effect. However, the interpretation of results must always account for other biotic or abiotic factors being likely to affect shoot growth. As a result, iG-Apex values from two different cultivars must be interpreted with caution, especially for moderate to high water constraint.

For operational use, iG-Apex is not appropriate for discriminating differences between moderate to strong water constraint and very strong water constraint situations, because in both cases iG-Apex values will be close to 0. Furthermore, it is worth noting that vine water status thresholds affecting vegetative growth are different from those affecting berry development or composition (Scholasch and Rienth, 2019). This would certainly be a limit to using iG-Apex to monitor vine water status during berry development and ripening. iG-Apex is therefore an approach that can be used at the beginning of the season when water stress is still relatively low, being less relevant for the in-season monitoring of fields undergoing more severe water stress.

iG-Apex is based on the observation of the vine's vegetative response to water stress. It provides information on the water stress experienced by the plant during the few days before the measurement, but not on vine water status at the exact moment of the measurement. This method is therefore particularly suitable for regions where summer rainfall is sparse and the onset of water stress is rather progressive. On the other hand, the relationship between iG-Apex and ψ_{PD} may not be valid in regions where summer rainfall is more frequent or in irrigated fields. iG-Apex therefore seems particularly suitable for use in regions with a Mediterranean climate and in non-irrigated situations. In this context, the study highlights the potential complementarity of iG-Apex and other reference methods like ψ_{PD} as decision support. The low material and human cost of iG-Apex measurements offers the possibility to carry out numerous measurements with a regular frequency and at many sites at the beginning of the season; i.e., before high or moderate water constraint occurs. In these conditions iG-Apex values are relevant and accurate even when performed by several operators on different cultivars. In the case of increasing water constraint and when vine water status monitoring requires accurate estimation, iG-Apex may be less appropriate, since it is less specific to water constraint. In these latter conditions, reference values like ψ_{PD} may be more appropriate. In commercial conditions, such a strategy is relevant since it has the advantage of both approaches either minimising operational constraints or maximising accuracy. Indeed, it would be necessary for the users to define an uncertainty threshold in order to help decide when to change from iG-Apex to a reference method, which will be based on the expected accuracy of vine water status monitoring.

For the practitioner, this strategy can also be based on empirical knowledge of spatial variability. Indeed, many studies have shown a significant spatial variability of vine water status at different spatial scales (Acevedo-Opazo *et al*., 2008; Taylor *et al*., 2009). This variability is stable over time, because it depends on stable environmental parameters, in particular the soil (Kazmierski *et al*., 2011). The monitoring of vine water status can then be implemented, preferentially in zones where the shoot growth has stopped on a major scale, and therefore where the vine is most likely to experience water stress early in the season. This strategy, implemented at field or farm scale, can also be implemented at a larger scale; for example, at a small regional scale, such as that of a cooperative. At these spatial scales, iG-Apex measurements can be collected each week by winegrowers and shared with their advisors. The latter can thus identify areas of early onset of water stress on which to focus their monitoring with ψ_{PD}.

Although the iG-Apex approach is relatively simple, it requires a number of tedious and time-consuming operations; i.e., counting, classifying apex, calculating iG-Apex values and recording the date and location of each measurement. To date, these operational considerations have limited the widespread use of this approach. The development of mobile applications simplifying all these operations (Pichon *et al*., 2021) should encourage the adoption of this approach by winegrowers and their advisors. This study could help operators use it as rigorously as possible.

Finally, future research is needed to: i) better characterise the relationship between the iG-Apex approach and other reference methods, particularly as a function of cultivar or group of cultivars and in relation to the evolution of soil water content and climate conditions, and ii) better explore potential relationships between secondary shoots and water constraint. This study did not differentiate primary and secondary shoots; however, it is widely accepted that water constraint does not influence them in the same way (Pellegrino *et al*., 2005). In some wine-growing regions, shoot trimming is carried out frequently, which favours the growth of lateral shoots. There is currently no reference in the literature that would allow this different response to be taken into account in order to adapt the iG-Apex calculation. This issue could be the subject of future investigations, should the method be developed in the wine industry.

CONCLUSION

A clear relationship was established between a method based on shoot growth observations (i.e., iG-Apex) and a reference method (predawn leaf water potential - ψ_{PD}) in order to indirectly assess vine water status in relation to vegetative growth. The results obtained using several cultivars and over several vintages conclude that iG-Apex can be used as an operational tool for monitoring vine water status in vineyard conditions. When compared to ψ_{PD}, this approach is valid between -0.2 MPa and -0.8 MPa. Although water stress is the main factor explaining variations in shoot growth, other factors, such as cultivar, rootstock, soil type, root depth or farming practices, affect the specificity of iG-Apex to water constraint, especially for high water stress. The high repeatability and reproducibility of iG-Apex makes it possible to share measurements made by several operators in order to carry out monitoring over large areas. At such a scale, it can be used relevantly and jointly with reference methods to increase the number and frequency of measurements at the beginning of the season, thus resulting in a more accurate estimation of plant water status on specific sites. This study also highlights interesting research questions that remain unexplored: i) Is it possible to improve iG-Apex by taking into account the specific response of secondary shoot growth to water stress? ii) How should the grape variety effect be accounted for in order to improve the iG-Apex method? Does the variety effect require each grape variety to be considered? and iii) Is the iG-Apex method relevant for the monitoring of berry development or berry composition?

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