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# Assessment of grapevine sap flow and trunk diameter variations in Mediterranean climate using time series decomposition

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## Summary

*Vitis vinifera* L. is a plant species that depends highly on temperature and water availability. Excessively hot and dry conditions can undermine growth and threaten grapevine performance. In these situations, grapevines activate self-regulating mechanisms to respond to water stress by prioritizing their survival through stomatal control and water redistribution. The monitoring of these mechanisms, through the measurements of the trunk diameter fluctuations and sap flow, was made for 'Touriga-Nacional' planted in the Douro Demarcated Region (NE Portugal), during the 2017 growing season. Seasonal and trend decomposition of the acquired data, as well as the assessment of the potential influence of meteorological variables was carried out, using locally estimated weighted regression and scatterplot smoothing. The objective behind this decomposition was to assess if the individual analysis of the periodic and inter-daily variations of the grapevine's trunk diameter fluctuations and sap flow could improve the understanding of their response to abiotic stress. The results have shown the methodology is efficient in extracting the different components and that their analysis is informative. It was possible to determine that the delay between the daily trunk diameter and sap flow periodic variations became shorter in time, suggesting the loss of water by transpiration is more easily observable under increasingly hotter and drier conditions. Furthermore, longer-term, inter-daily variations at the trunk are highly correlated with those of relative humidity, evidencing the impact of air moisture on their water status. Such findings justify the implementation of locally weighted regression and scatterplot smoothing (STL) in the operational processing of sap flow and trunk diameter time series in the control of grapevine water status, in the case of optimization of vineyard management by wine growers.

## Keywords

**Viticulture, Plant-based sensors, Seasonal-trend decomposition, Douro Demarcated Region**

## Introduction

Grapevine phenology depends primarily on atmospheric conditions (Fraga *et al.*, 2012, Dinis *et al.*, 2022). Grapevines are sensible plants and any disruption caused by radiative, thermal, and water stresses may affect the quality of the grapes produced (Malheiro *et al.*, 2020). In situations of extreme abiotic stress, grapevines can sacrifice, to a certain extent, their vegetative growth and concentrate on their vital organs to ensure survival (Hsiao, 1973, Chaves, 1991). Disruptions such as these can occur in wine regions located in southern European countries such as Italy, Portugal, and Spain, which tend to have long-growing seasons, as well as hot and dry summers (Ferreira *et al.*, 2012, Dinis *et al.*, 2014). Furthermore, extreme weather events, such as heatwaves or prolonged droughts, are becoming more frequent (Chaves *et al.*, 2010, Bernardo *et al.*, 2018) with the advent of climate change (Bernardo *et al.*, 2018, Fraga *et al.*, 2020, Dinis *et al.*, 2022).

Grapevines have mechanisms to handle high temperatures and water stress, such as stomatal control to reduce transpiration and nocturnal rehydration (Cuevas *et al.*, 2010, Fernández *et al.*, 2011, Fernández, 2017, Meng *et al.*, 2017, Fraga *et al.*, 2020). These mechanisms can be monitored continuously by measuring the variations of a grapevine's sap flow (SF) and trunk diameter variations (TDV), respectively, by the use of non-destructive sensors installed at a trunk (Cifre *et al.*, 2005, Montoro *et al.*, 2012, Meng *et al.*, 2017). The monitoring allows for the evaluation of the impact of the various environmental variables and ongoing vineyard performance (Fernández, 2017, Meng *et al.*, 2017). A coupled analysis of these mechanisms has been done for different crops, such as peach and olive trees (Cohen *et al.*, 2001, Conejero *et al.*, 2007, Cuevas *et al.*, 2010, Fernández *et al.*, 2011), but for grapevines as well (Escalona *et al.*, 2002, Baert *et al.*, 2013, Oliveira *et al.*, 2017). More recently, an experiment was conducted in the Douro Demarcated Region (DDR), NE Portugal, to compare the performance of the aforementioned self-regulating mechanisms of 'Touriga-Nacional' grapevines trained to spur-pruned cordon and Guyot systems (Malheiro *et al.*,



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2020). Results clearly showed how the SF responds to solar radiation and a rise in temperature from early morning to late afternoon. TDV would respond inversely to SF, but it would also evidence the plant's natural growth and the response to meteorological variables. The amplitude of the daily variations flattened as pedoclimatic conditions got harsher during the later phenological intervals.

The present study has set out to further explore the TDV and SF measurements carried out by Malheiro *et al.* (2020), namely those associated with the cordon (the most widely used training system in the DDR) grapevines. The objective was to improve the understanding of the physiological response of 'Touriga-Nacional' grapevines to abiotic stress. An exploratory analysis of the acquired time series was done using locally weighted regression and scatterplot smoothing, STL, (Cleveland and Devlin, 1988). This method is a filtering tool that decomposes time series into three additive components: periodic, inter-daily, and residual. The analysis of these components individually allows for a more detailed understanding of the data, in comparison to a raw analysis. There are other ways to extract the different types of signals in a time series, such as linear regression (linear trends) or the Fourier transform (periodic signals), but the chosen method can deal with multifaceted data in a simple, efficient, computationally undemanding way, and has been thoroughly used in the natural sciences (Chaloupka, 2001, Isotta *et al.*, 2008, García-Mozo *et al.*, 2014, Lafare *et al.*, 2016). Besides the coupled analysis of each of the components of TDV and SF, the inter-daily relation with meteorological variables, namely solar radiation (SR), mean temperature (Tg), and relative humidity (RH), was also investigated to understand which of them were more impactful and to see if they can be reliable predictors in stepwise regression models.

Henceforth, in Section 2, the material and methodologies followed in this study are described. Section 3 is devoted to the presentation of the main results. Section 4 offers a discussion of the results. Lastly, section 5 presents the main conclusions.

## Material and Methods

### *Study area*

The aforementioned experiment was conducted in a commercial vineyard, located in the Douro Demarcated Region (41°04'18" N, 7°04'51" W, 160 m), Portugal (Figure 1). The 'Touriga-Nacional' grapevines there existing were planted in 2011 and are grafted onto 110 Richter rootstocks with a spacing of 2.2 per 1.0 m and E-W orientation. The TDV and SF measurements were made during the 2017 growing season (Malheiro *et al.*, 2020). The measurements were divided into three parts, however, to analyze individually the distinct variabilities that occurred during the post-flowering,

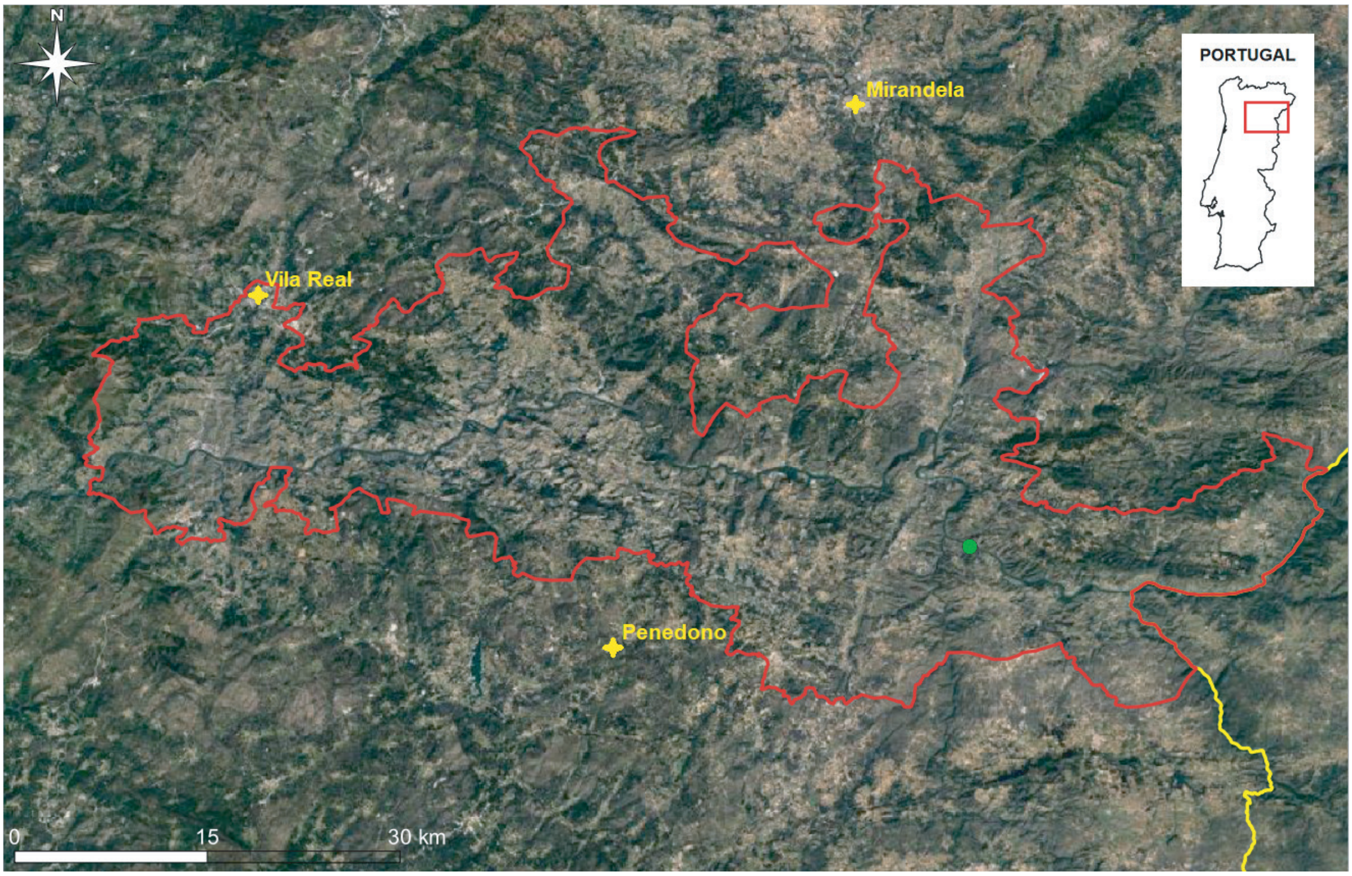


Figure 1: Location of the study area. Red lines bound the area of the Douro Demarcated Region in NE Portugal. The green dot indicates the location where measurements were made during the 2017 growing season. Yellow stars mark nearby cities and towns. Yellow lines represent the border between Portugal and Spain.

post-veraison, and mid-maturation to ripening phenological intervals.

The meteorological measurements were made by a weather station (IMT280, iMETOS, Pessl Instruments, Weiz, Austria) therein installed. Several variables were measured, at an hourly rate, but only SR, Tg, and RH were considered herein. Table S1 shows the maximum, minimum, and mean values registered for each of the variables in the three periods. The summer of 2017 was particularly dry and hot at the DDR, with maximum temperatures reaching > 40 °C. Furthermore, to guarantee plant survival, supplemental water was supplied by drip irrigation during the measurement period, amounting to up to 50 mm. The vineyard's soil is mostly composed of schist soils with a loam-dominated texture, classified as surribi-aric anthrosol (Agroconsultores and Coba, 1991). More details can be found in the preceeding study (Malheiro *et al.*, 2020).

### *Trunk diameter and sap flow measurements*

To measure TDV, linear variable differential transformers (Solartron Metrology Model DF ± 2.5 mm, accuracy ± 10 µm, Bognor Regis, United Kingdom) were used. This equipment converted the rectilinear movement of the trunk into digital signals that were subsequently processed as required (Katerji *et al.*, 1994, Zweifel *et al.*, 2000). It was installed at three grapevines, at their main trunk, and to avoid its thermal expansion and wetting, the grapevines were covered with thermo-protected silver sheets. Measurements were made at a period of 30 s, using a data logger (CR100 Campbell with an AM16/32 multiplexer) that was programmed to store the mean of the TDV values acquired every 5 min by each sensor.

To measure SF, the thermal dissipation technique was used (Granier, 1985, Granier and Gross, 1987). This technique makes use of the temperature gradient between probes set up at two points along the grapevine's trunk. One of the probes is heated and when SF occurs, heat is partially dissipated and the temperature gradient is reduced (Xie and Wan, 2018). Five grapevines were chosen and were thermally insulated from the exterior to avoid the formation of naturally occurring temperature gradients. Four non-heated sensor-pairs were also installed in other selected grapevines, to account for natural thermal gradients. The natural temperature gradients measured at the unheated sensors allowed for the correction of the heated ones. All measurements were made within a 30 s period and registered also using a data logger (CR100 with an AM25T multiplexer, Campbell Scientific Inc., Shepherd, United Kingdom), which was programmed to store the mean SF values acquired every 5 min by each sensor. Further details on the SF and TDV measurements can also be found in Malheiro *et al.*, 2020.

### *Data processing*

SF, TDV, and the considered meteorological variables were processed using the 'STL' function included in the R-package 'stats' (v. 3.6.2), using the default settings (Cleveland *et al.*, 1990). STL stands for 'Seasonal-Trend Decomposition by Loess' and the function employs a series of smoothing operations using locally weighted regression and scatterplot smoothing, Loess, (Cleveland and Devlin, 1988). The procedure is made by iteratively fitting regression models to segments of the data from which new data points are generated. The size of the data segments will be smaller for seasonal extraction and bigger for trend extraction. To avoid the effect of outliers, weights are attributed to each of the data points, depending on the distance they have to each other. Once the procedure is complete, the original time series are decomposed into additive components, namely the periodic, inter-daily, and residual components. The periodic component corresponds to the variations which oscillate periodically. The inter-daily component represents the variations that can last several days and have no periodicity. Lastly, the residual component constitutes the residual of the data after the previous components have been removed from the original data. This component was not analyzed and is not presented in this study.

The use of the 'STL' function requires that the data have no missing values. To fulfil this requirement, the time series were imputed using the R-package 'forecast' (v. 8.13) (Hyndman and Khandakar, 2008). During this operation, it was calculated that 0.19% of the TDV time series values are missing values and that 0.05% of the SF time series values are missing values. Furthermore, the linear trend of the data was removed as well by subtracting a linear regression model from the data. This was a necessary step to ensure the inter-daily variability could be properly studied. Lastly, the decomposed datasets were Box-Cox transformed (Box and Cox, 1964) to increase normality as well as feature-scaled for improved visualization.

## Results

### *Raw data processing*

The SF and TDV field measurements are divided into three phenological intervals: post-flowering, post-veraison, and mid-maturation to ripening. Looking first at the raw data, both variables have a daily cycle, evidencing the influence of solar radiation (Figure 2a-c). The amplitude of these cycles decreases substantially between each phenological interval due to the progressive lack of water (Malheiro *et al.*, 2020). During the post-flowering interval, TDV has a dominating positive trend, evidencing the natural growth of the grapevine. The effect of this growth is no longer visible in the last two intervals, with TDV retreating to its initial levels and eventually stabilizing. This stabilization is part of the natural phenological development of the grapevine (Intrigliolo and Castel, 2007). As for SF, it does not exhibit any clear long-term trends. When looking at the transformed data without the linear trend, inter-daily variations become clearer (Figure 2d-f). The effect of the irrigation events, for example, is now visible, increasing both TDV and SF, but especially TDV. Other effects are also visible and will be investigated in the next sections.

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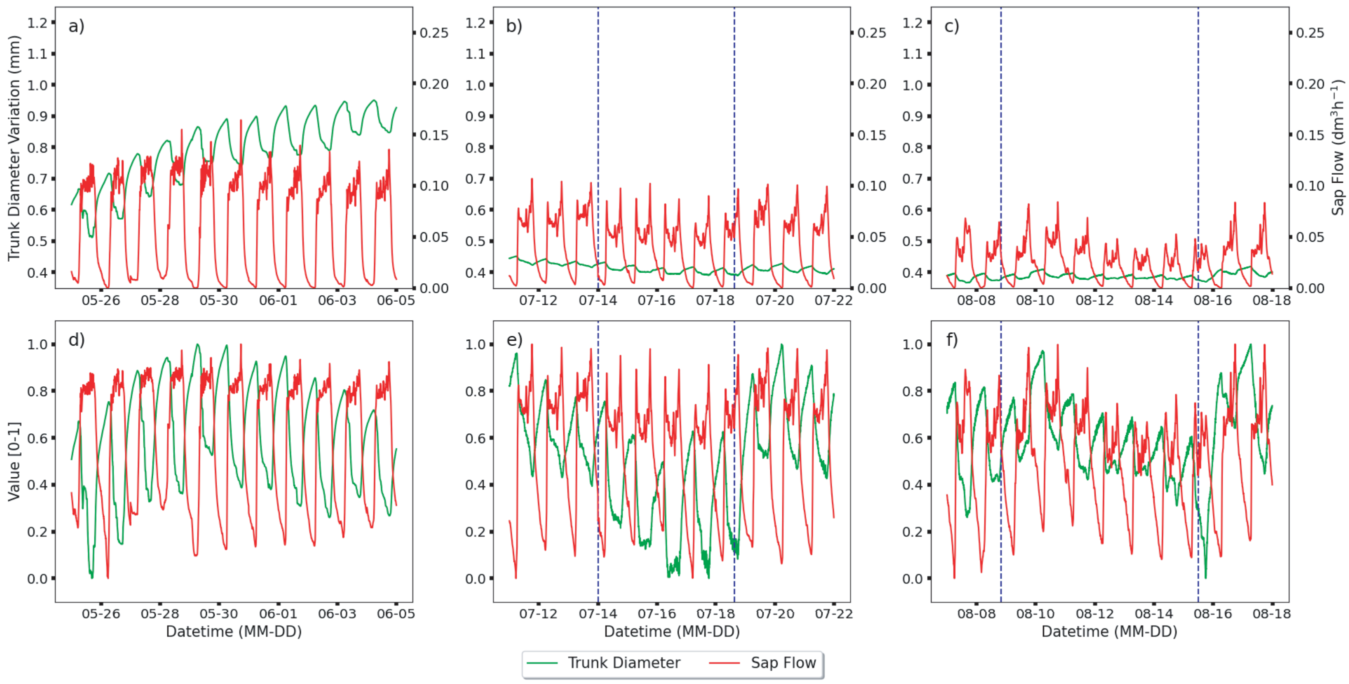


Figure 2: Hourly time series of trunk diameter variations and sap flow in 'Touriga Nacional' grapevines for [a, d] post-flowering, [b, e] post-veraison, and [d, f] mid-maturation to ripening phenological intervals in 2017. Top row: Raw data. Bottom row: Box-Cox transformed and feature-scaled hourly time series without linear trend. Blue dashed lines represent irrigation events.

## *Periodic signals*

Periodic TDV and SF clearly show a daily cycle caused by SR (Figure 3). To verify the daily period, pseudo-spectral estimates were obtained with MATLAB using the MUSIC algorithm (Wang *et al.*, 2005). This method does an eigenspace analysis of signals in the time domain, according to Schmidt (1986), and estimates the periods with the highest power in decibels. In the case of TDV and SF, estimates indicate the main oscillations have a period of close to 24 hours, as expected (Figure 4). These have opposite phases because SF results in a decrease in TDV. Furthermore, cross-correlation of these variables indicates different delays for the different phenological intervals (Figure S1). By counting the time lags where correlation is maximized, it is possible to estimate that in the post-flowering interval, the delay between TDV and SF is approximately 1 h 25 min. In the post-veraison interval, the delay is approximately 1 h, whereas the delay is approximate-

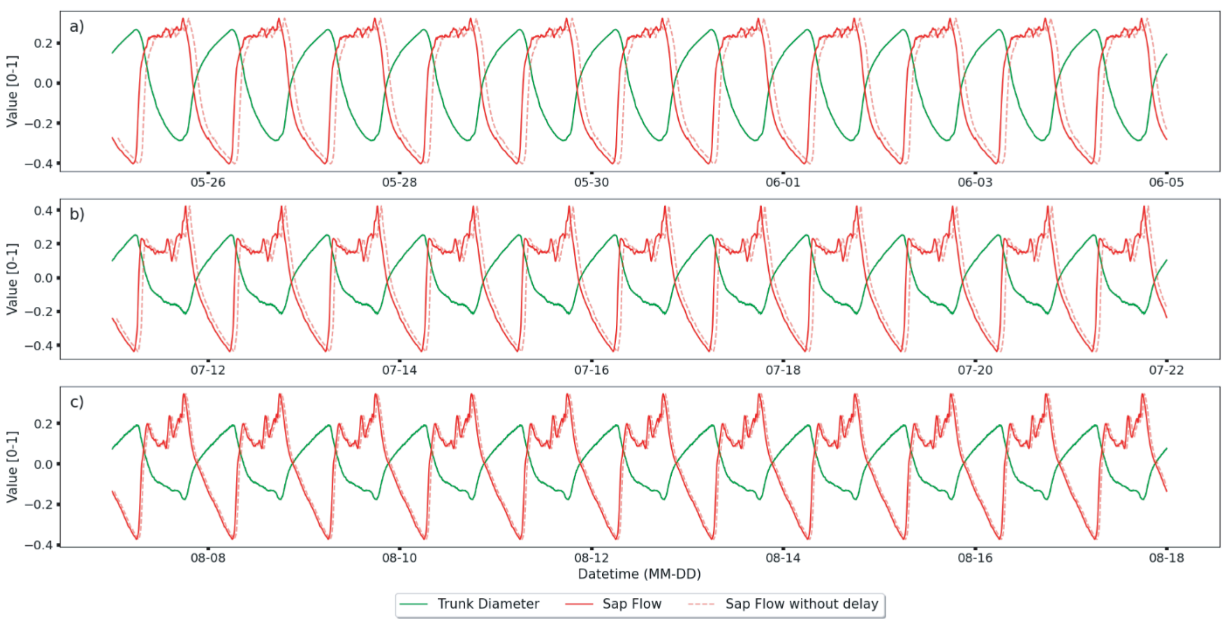


Figure 3: Periodic component of the normalized and Box-Cox transformed hourly time series, without linear trend, corresponding to a) post-flowering, b) post-veraison, and c) mid-maturation to ripening intervals. Light red dashed lines represent sap flow time series corrected for a delay concerning the trunk diameter variation: (a) 1 h 25 min, (b) 1 h, and (c) 25 min.

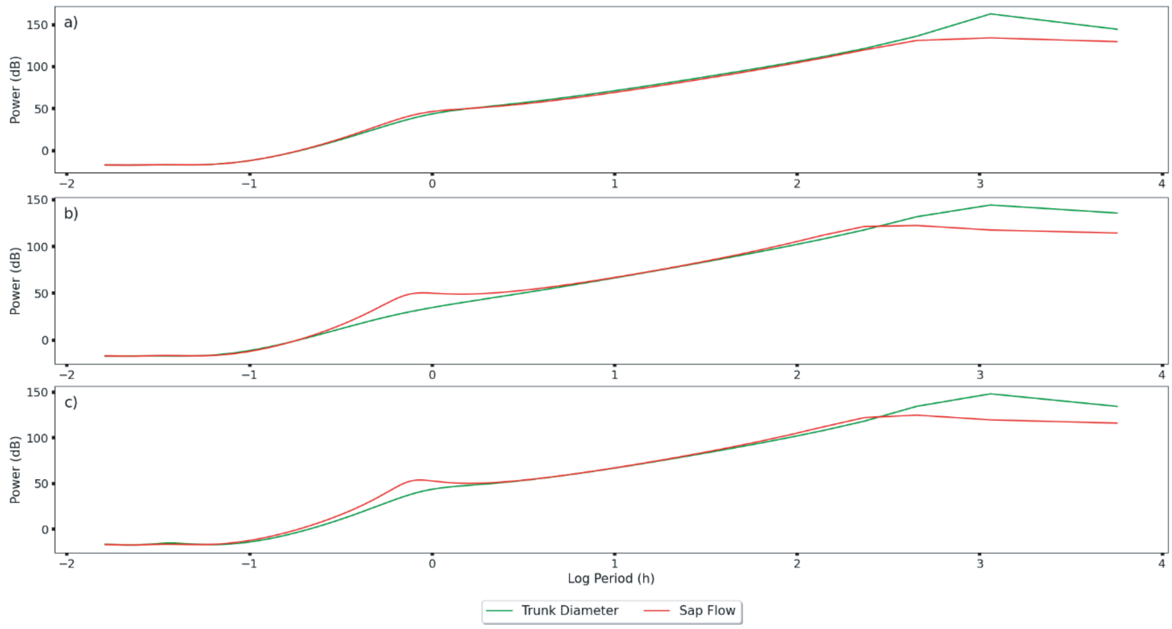


Figure 4: Pseudospectral estimates for trunk diameter variations and sap flow in the a) post-flowering, b) post-veraison, and c) mid-maturation to ripening intervals.

ly 25 min during the mid-maturation and ripening. The delay removal improves the correlation, as indicated by the Pearson correlation coefficients (*r*) between SF and TDV (Table 1), at a significance level (*p*-value) of 5%.

### *Inter-daily variations*

The inter-daily variability of the TDV and SF as well as of the considered meteorological variables is visible in Figure 5. TDV, RH, and Tg all exhibit inter-daily moderate to high variability, SF and SR exhibit low to moderate variability. The correlation between TDV and SF with the different meteorological variables was assessed (Table 2). The correlation coefficients indicate TDV is strongly correlated with RH and Tg and weakly correlated with SR (*p*-values < 0.05). As for SF, coefficients indicated it is weakly correlated with all of the meteorological variables. Furthermore, some of the coefficients have *p*-values above 0.05, indicating they are not statistically relevant as well.

Stepwise regression modelling was carried out as well to verify if it is viable to model the inter-daily TDV and SF during the post-flowering and post-veraison intervals, in terms of the meteorological variables (Table S2). The effects of irrigation are significant in the post-veraison interval and dwarf the effects that could be attributable to meteorological variables. Thus, all the data after that event, including the mid-maturation to ripening interval, were left out of the modelling. The model $R^2$ values are high for the TDV models and low for SF. Corresponding *p*-values are below 0.05, deeming them statistically significant. This indicates that the inter-daily TDV can be successfully estimated from the considered meteorological variables but not SF.

## Discussion

As previously stated, high temperatures and low precipitation characterized the summer of 2017 in the DDR, particularly during the later phenological intervals (Malheiro *et al.*, 2020). This led to grapevine water stress, which was reflected in the raw TDV and SF data, gradually becoming less expressive due to lower water availability and stomatal control. The effects of these occurrences on grapevines have been fairly discussed (Rodrigues *et al.*, 1993, Escalona *et al.*, 2002, Intrigliolo and Castel, 2007, Blum, 2009, Escalona and Ribas-Carbó, 2010, Oliveira *et al.*, 2017, Bonada *et al.*, 2018). Further study of the data using STL time series decomposition has provided new insights and is discussed in the following sub-chapters.

Table 1: Pearson correlation coefficients and correspondent p-values for correlation between periodic trunk diameter variations and sap flow in the different phenological intervals, with and without delay correction.

| | Post-Flowering | | Post-Veraison | | Mid-Maturation to Ripening | |
|---|---|---|---|---|---|---|
| | With Delay | Without Delay | With Delay | Without Delay | With Delay | Without Delay |
| r | -0.85 | -0.94 | -0.87 | -0.94 | -0.93 | -0.95 |
| p-value | 4.38e-83 | 6.30e-140 | 2.77e-92 | 2.23e-135 | 2.91e-131 | 1.49e-146 |

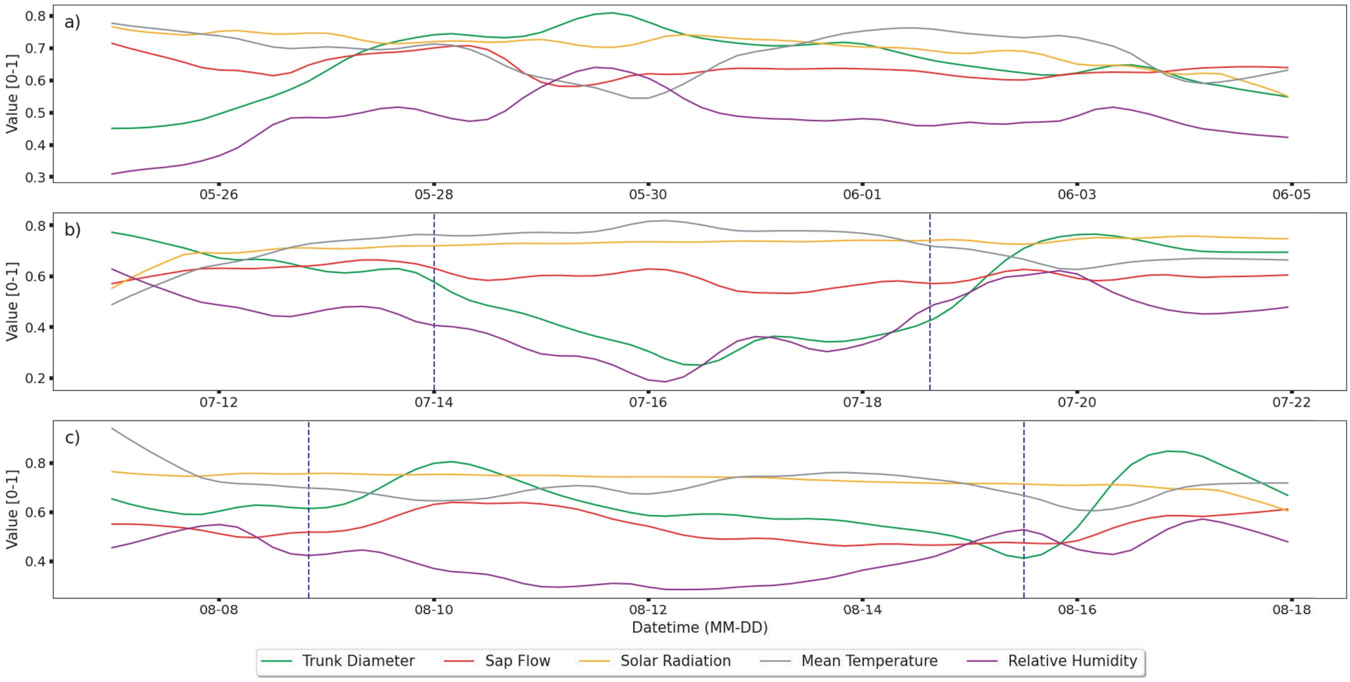


Figure 5: Inter-daily component of the normalized and Box-Cox transformed hourly time series, without linear trend, corresponding to a) post-flowering, b) post-veraison, and c) mid-maturation to ripening intervals. Blue dashed lines represent irrigation events.

## *Periodic component*

The STL decomposition successfully extracted the periodic component of TDV and SF measurements without showing any trend or random walk signal (Figure 3). This confirms the usefulness of the method as was demonstrated previously by Xia *et al.* (2019), who were able to extract the annual groundwater level variation of the Tarim basin in China. In the present study, it was possible to extract the daily cycle of both variables, prompted by the diurnal solar cycle. Cross-correlation of the variables revealed that the delay between TDV and SF became lower as conditions became hotter and drier at each phenological interval (Figure S1). This observation seems to indicate that a grapevine's trunk will reflect the loss of water through transpiration faster under increasingly hot and drier conditions. Such an indication can help the detection of water stress in a vineyard by monitoring the change in the delay between TDV and SF.

Table 2: Pearson correlation and correspondent p-values relating inter-daily trunk diameter variations and sap flow with meteorological variables.

| Meteorological Variables | Trunk Diameter Variations | | | | | |
|---|---|---|---|---|---|---|
| | Post -Flowering | | Post-Veraison | | Mid-Maturation to Ripening | |
| | r | p-value | r | p-value | r | p-value |
| Solar Radiation | 0.07 | 0.21 | -0.30 | 4.87e-07 | -0.09 | 0.12 |
| Mean Temperature | -0.46 | 1.65e-15 | -0.85 | 1.86e-77 | -0.22 | 3.37e-04 |
| Relative Humidity | 0.89 | 1.68e-91 | 0.87 | 6.79e-84 | 0.07 | 0.21 |
| **Meteorological Variables** | **Sap Flow** | | | | | |
| | Post -Flowering | | Post-Veraison | | Mid-Maturation to Ripening | |
| | r | p-value | r | p-value | r | p-value |
| Solar Radiation | 0.23 | 2.53e-04 | -0.29 | 6.00e-04 | -0.02 | 0.76 |
| Mean Temperature | 0.31 | 1.17e-07 | -0.12 | 0.05 | -0.22 | 2.32e-04 |
| Relative Humidity | -0.45 | 3.21e-15 | 0.21 | 6.80e-04 | -0.06 | 0.31 |

### *Inter-daily variations*

For the inter-daily variability, the STL decomposition also extracted successfully the smaller-scale trends within the data (Figure 5). Such extraction has also been done by Aguilera *et al.* (2015), for example, to analyze the trends of Mediterranean cumulative temperatures and olive tree pollen emissions, between 1993 and 2011. The considered timeframe in the present study is shorter but informative. The extracted trends allowed for a better understanding of the relations between TDV and SF with considered meteorological variables. Until the second irrigation event, the inter-daily variability of RH follows perfectly that of the TDV, which is corroborated by the high and positive correlation between the two variables (Table 2). This indicates the importance of air moisture in predicting the state of a grapevine's trunk, particularly during dry spells. The observed Tg had a considerable (negative) correlation with the TDV during the post-veraison but not so considerably during the post-flowering interval. Furthermore, stepwise modeling attributes RH's main role in predicting the inter-daily variability of TDV during both considered intervals (Table S2). Thus, these results highlight that grapevines are sensitive to dryness, and RH can highly affect the water status of this crop under dry conditions. As for SF, its correlation with the meteorological variables is low and its stepwise models do not have significant predictive power. The reason for this behavior is probably because the nature of SF does not translate well into wide, inter-daily variability, due to the sharp increase observed in the early morning and the sharp decrease observed in the late afternoon, which confer it a step-like variability different to that of TDV, which is more sine-like. Similar observations were documented by Herzog *et al.* (1995), for example. Therefore, SF cannot be used to assess indirectly the longer-term evolution of grapevine water status.

### *Limitations of the study and opportunities*

One of the limitations of this study is the fact that only one dataset, corresponding to one year's growing season, was analyzed. Although statistical work deemed much of the results statically significant, it would be important to verify if what happened during 2017 was not an exception to the rule, but the rule, so conclusions could be more robust. Furthermore, STL data decomposition was undertaken using the default options of the selected R-package, and, thus, different calibrations were not tested to assess how the results would eventually change. Further experimentation could increase confidence in the results and/or, perhaps, reveal other aspects of the data that were not clear using the default options. Lastly, reviewed studies indicate grapevine varieties have different stomatal responses to water stress, which influences SF (Gambetta *et al.*, 2020). However, studied varieties are limited and, thus, it would be important to enlarge the body of work on this issue to ensure proper varietal selection.

## Conclusions

Grapevine water management is crucial, such as when a vineyard can suffer from a lack of water under harsh climatic conditions. In this effort, the monitoring of SF and TDV are valuable tools to identify situations where severe water stress is occurring in a vineyard. Previous analysis of these variables in the DDR, during the hot and dry summer of 2017, confirmed this idea. In the present study, further investigation using STL data decomposition has provided an improved understanding of what can be asserted from a grapevine's TDV and SF concerning its water status. The methodology proved successful in extracting the different components of the data and two major findings were made: 1) the delay between SF and the TDV daily cycles becomes lower as conditions get hotter and drier in the field, evidencing, on one hand, the higher water deficit at each phenological interval, and on the other hand, a more prompt response from the grapevine to the loss of water (through SF), 2) the longer-term inter-daily variability highlights how RH can be an important determinant of the trunk diameter variation, and by proxy, the atmospheric demand of the grapevine for water, under dry conditions. Temperature and solar radiation also play a part, mainly during the drier post-veraison interval, but RH is the main driving variable, as evidenced by the stepwise regression approach. Hence, these findings suggest that the integration of STL decomposition in the SF and TDV post-processing could be considered useful to winegrowers who are interested in fine-tuning the performance of their vineyards. However, the reproducibility of the results has yet to be verified and different grapevine varieties and wine regions should be studied.

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## Contribution to the field statement

The wine industry is an important socioeconomic sector in southern Europe. The consumption of wine has a long tradition, and its production contributes significantly to regional economies in various ways. Thus, its long-term sustainability should be assured. In this sense, the present research seeks to improve the understanding of how 'Touriga-Nacional' – an important grape variety in Portugal – responds to hot and dry weather, by looking in detail at continuous measurements of sap flow and trunk diameter variations during the growing season. This was done successfully by using a time series processing tool, called "Seasonal and Trend decomposition using Loess", which decomposes time series into additive components that can be analyzed individually. The use of methodology has not been used yet in the context of sap flow and trunk diameter variation analysis, thus, it constitutes a novelty. Ultimately, the information here imparted seeks to help wine growers in their decision-making in regards to managing water stress in vineyards, so they can assure their activity in the long run.

## Conflicts of interest

The authors declare that they do not have any conflicts of interest.

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