Modelling vine water stress during a critical period and potential yield reduction rate in European wine regions: a retrospective analysis

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Abstract

Most European vineyards are managed under rainfed conditions, where seasonal water deficit has become increasingly important. The flowering-veraison phenophase represents an important period for vine response to water stress, which is seldom thoroughly evaluated. The study aims to quantify the flowering-veraison water deficits using the Crop Water Stress Indicator (CWSI) and assess the seasonal water stress driven potential Yield Lose Rate (YLR) for major European wine regions over the period of 1986–2015. The assessment methodology is based on the conventional gridded-based crop modelling for regional mapping using the viticulture model STICS. The findings suggest wine regions with stronger flowering-veraison CWSI tend to have higher potential YLR. However, contrasting patterns are found between wine regions in France-Germany-Luxembourg and Italy-Portugal-Spain. Advanced phenophase over 1986–2015 may result in slightly alleviated CWSI in wine regions of Italy-Portugal-Spain, probably because of more exposure to spring precipitation. However, this can lead to insignificant changes in CWSI in those of France-Germany-Luxembourg with relatively even seasonal precipitation distribution. Overall, such a retrospective analysis might provide new insights toward better management of seasonal water deficits for important European rainfed vineyards.

Introduction

Most of the European wine-growing regions are currently cultivated under rainfed conditions, as a result of policy restrictions and concerns for sustainable water use (Costa et al., 2016). In recent decades, the water deficit has become increasingly important in rainfed European wine regions. In particular, water deficits combined with high temperatures in summer during the berry ripening period can represent a major limiting factor for vineyard productivity in Mediterranean wine regions (Cornélis van Leeuwen et al., 2018). Mild water deficits favors the berry accumulation of sugar and some phenolics (e.g. anthocyanin), whereas severe water stresses can lead to significantly reduced berry quality (sugar, aroma) and grape yield (Cornelis van Leeuwen et al., 2009; Cornélis van Leeuwen et al., 2018). Water shortage before veraison can have strong negative impacts on leaf growth, berry weight and final yield per vine (Gambetta et al., 2020; Cornélis van Leeuwen et al., 2018). The flowering-veraison phase proves to be an important period for vine growth response to water deficits in terms of berry weight and yield formation process (M C Ramos & Martínez-Casasnovas, 2014; María Concepción Ramos et al., 2020). For instance, grape yield is found to be particularly sensitive to water availability of the bloom-veraison period, during which a yield increase of about 46 kg/ha per mm water input is observed for Cabernet Sauvignon (CS) (M C Ramos & Martínez-Casasnovas, 2014). Few studies have investigated vine water deficits during the flowering-veraison period and their impacts on potential vine productivity. Hence, our study was carried out for major European wine regions over the recent-past period (1986–2015), aiming to (i) assess vine drought stress conditions exclusively during the flowering-veraison phase based on the Crop Water Stress Indicator (CWSI); (ii) assess the potential Yield Lose Rate (YLR) due to seasonal cumulative water stress (yield refers to the mean cluster weight at harvest). The possible link between CWSI and YLR is analyzed; (iii) investigate in a what-if scenario, in which the flowering-veraison phase is assumed to be advanced (5–25%) to emulate global warming under historical conditions (1986–2015), with the aim to evaluate if the vine water deficits can be alleviated or not.

Materials and methods

The overall methodology is based on the gridded-crop modelling using a process-based viticulture model STICS (Brisson et al., 2009), considering observed weather, soil and crop data etc. STICS has been extensively calibrated for simulating the flowering (BBCH65) and/or veraison (BBCH81) stages across 38 sites for 10 different grapevine varieties, in order to better simulate a phase-dependent crop water deficit (Yang et al., 2022). For the gridded input datasets, their names, variables covered and spatial resolutions etc., have been summarized in **Table 1**. Details on how they were extracted and assimilated into the crop model could be found in Yang et al. (2020, 2022). Besides, the mathematical formula to calculate the CWSI was as follows:

$$\mathrm{CWSI} = 1 - \frac{ET}{ET_{max}}$$

where ET and ET_{max} were daily actual and maximum evapotranspiration respectively, deriving from model simulations. They were calculated based on the Shuttleworth and Wallace (S-W) module of STICS, which characterized the soil-plant-atmosphere system with a resistance network, proving to be effective in explaining the canopy energy budget (Brisson et al., 1998, 2009). It integrated the effect of climate, soil and crop characteristics, which had been widely applied for drought monitoring and assessment (Wu et al., 2019; Yang et al., 2022; Zhu et al., 2021). The potential YLR (%) was computed as follows:

$$\mathrm{YLR}(\%) = \left(1 - \frac{Y_{stress}}{Y_{potential}}\right) \times 100\%$$

where Y_{stress} and $Y_{potential}$ were the potential cluster weight (g) at harvest simulated with and without water stress, respectively. $Y_{potential}$ can also be interpreted as the yield under full watered conditions while keeping the other field managements optimal (van Ittersum et al., 2013). Y_{stress} represented the water-limited potential yield, in which $Y_{potential}$ is additionally limited by seasonal water supply (van Ittersum et al., 2013). The what-if scenario is built up by modifying the calibrated phenology parameters of each grid point, at which the required thermal demand (e.g. GDD) for flowering and veraison stage was simultaneously reduced by 5%, 15% and 25% respectively. As such, the flowering-veraison phase was assumed to be shifted earlier by 15–25%, which were to emulate the effects of global warming under historical conditions (1986–2015).

Results and discussion

The median CWSI over 1986–2015, generally varies in the range of 0–0.5 (slight to moderate drought) in wine regions of France-Germany-Luxembourg (F-G-L), to 0.5–1.0 (severe to extreme drought) in those of Italy-Portugal-Spain (I-P-S) (**Figure 1a**). Wine regions prone to a severe drought risk of the flowering-veraison phase (CWSI>0.75), are identified as those in the Iberian Peninsula (except north-western Portugal), southern areas in France (Languedoc, Provence, Rhone) and Italy (Apulia, Sardinia, Sicily) (**Figure 1a**). These results can be associated with the spatial precipitation distribution, where higher annual precipitation is expected in wine regions of F-G-L than those of I-P-S. For rainfed Mediterranean viticulture, most of the berry growth and ripening periods are frequently exposed to conditions of high temperature and soil water deficits, which are particularly pronounced for the Iberian Peninsula (Costa et al., 2016). However, it shall be cautioned that CWSI calculations rely on the S-W resistive model for estimating evapotranspiration (Brisson et al., 1998), which might require additional verifications. But available lysimeter measurements with quality records are scarce across a large geographic scale. The quantified median YLR over 1986–2015 shows a similar spatial pattern as that of CWSI, with higher YLR in I-P-S countries than in F-G-L countries (**Figure 1b**). For wine regions in F-G-L, a negligible-to-moderate YLR (<30%) (**Figure 1b**) is detected with slight-to-moderate drought conditions (CWSI<0.5) (**Figure 1a**), whereas substantial YLR (>40%) (**Figure 1b**) is found in those of I-P-S countries where CWSI is generally severe-to-extreme (>0.5) (**Figure 1a**). These results reveal wine regions with stronger flowering-veraison CWSI tend to have higher potential YLR, particularly for the identified drought-prone (CWSI>0.75) regions. The flowering-veraison phase represents a crucial period for yield responses to water stress, which has been observed in the fields (M C Ramos & Martínez-Casasnovas, 2014;

María Concepción Ramos et al., 2020) and successfully reflected in our simulations (**Figure 1**). Our study suggests the relationship is most likely seasonal-climate dependent and subsequent research shall explore if such a relationship is particularly susceptible to the influence of extreme weather conditions and genotypic characteristics (see Yang et al., (2022) for details). On the other hand, it should be emphasized that although gridded-crop modelling already incorporated phenology data, the variety-specific growth parameters, such as potential leaf growth and photosynthesis capacity, are not adjusted locally to reflect yield response to water deficits. Therefore, some levels of uncertainties exist in the simulated magnitude of YLR.

Advanced flowering-veraison phenophase by 5–25% over 1986–2015 indicates only small variations of CWSI, ranging from –0.05 to 0.05 across all wine regions (**Figure 2**). A slight increase in CWSI is found for wine regions in F-G-L countries, but without statistical significance (**Figure 2a–c**). Only up to 25% early shift of the flowering-veraison phase, significant ($p<0.05$) changes of CWSI occur, where slight reductions (alleviations) of vine water deficits have been found in wine regions of I-P-S, mainly in those drought-prone regions (CWSI>0.75) (**Figure 2c**). It suggests the shifted phenophase seems to have limited effects on the alleviation of flowering-veraison vine water deficits. For wine regions in I-P-S, slight water deficits alleviation can be attributed to shifted phenophase towards the spring season, where a significant fraction of annual rainfall can occur before the flowering stage (M C Ramos & Martínez-Casasnovas, 2014). This might not be effective for those of F-G-L countries with a relatively even seasonal precipitation distribution. Moreover, the early shifted flowering-veraison phase can lead to cooler temperatures with reduced evaporative demands (ET_{max}), thus contributing to reduced CWSI in wine regions of I-P-S (Costa et al., 2016). Such effects can also be expected for those of F-G-L, but the magnitude can be comparatively smaller. The overall limited effects on alleviation of CWSI can be mainly explained by the considerable inter-annual variability of local climate (e.g. precipitation) across all wine regions (Yang et al., 2022). Further step shall investigate if such effects are more limited under extreme (warm & dry) or normal climates, as well as the associated mechanism.

Table 1. List of employed datasets in gridded-crop modelling

Dataset category	Dataset name	Variables covered	Approximate horizontal space resolution	Access URL	Supporting references
Climate datasets	E-OBS	Temperature; Precipitation	11.1 km	https://www.ecad.eu	(Cornes et al., 2018)
	ERA5-Land	Radiation; Wind speed; Vapour pressure	11.1 km	https://cds.climate.copernicus.eu	(Muñoz Sabater, 2019)
Terrain dataset	EU-DEM	Surface slope degree	25 m	https://land.copernicus.eu/imagery-in-situ/eu-dem/eudem-v1.1?tab=metadata	/
Soil datasets	HWSD	Particle size distribution; Bulk density; Surface dry albedo etc.	1 km	https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/	(FAO/IIASA/ISRIC/ISSCAS/JRC, 2012)
	EU-SoilHydroGrids	Soil volumetric water content at field capacity and wilting point etc.	1 km	https://esdac.jrc.ec.europa.eu/content/3d-soil-hydraulicdatabase-europe-1-km-and-250-m-resolution	(Tóth et al., 2017)
Plant dataset	Clim4Vitis	Flowering stage (BBCH65); Veraison stage (BBCH81)	*in-situ*	https://clim4vitis.eu/	(Clim4Vitis, 2021)
	PEP725		*in-situ*	http://www.pep725.eu/	(Templ et al., 2018)
	IPHEN		100 m	http://cma.entecra.it/iphen/index_EN.html	(Mariani et al., 2013)

Conclusion

Water stress of a drought-sensitive period is assessed for European rainfed vineyards. Wine regions prone to a high flowering-veraison drought risk are identified, which are mainly in southern Mediterranean Europe. Our findings suggest the flowering-veraison water availability is critical to the potential vine productivity, but is dependent on local soil, climate conditions and genotypic characteristics. With global warming, anomalously warm years can frequently occur, resulting in an early-shift of the flowering-veraison phase. Therefore, our what-if scenario analysis could be useful as the reference results based on historical climatology, which can facilitate the development of water-stress diagnostic tools for local vineyards. Consequently, winegrowers can take advantage of the flowering-veraison time window to better control the potential yield level according to the rule of each DO.

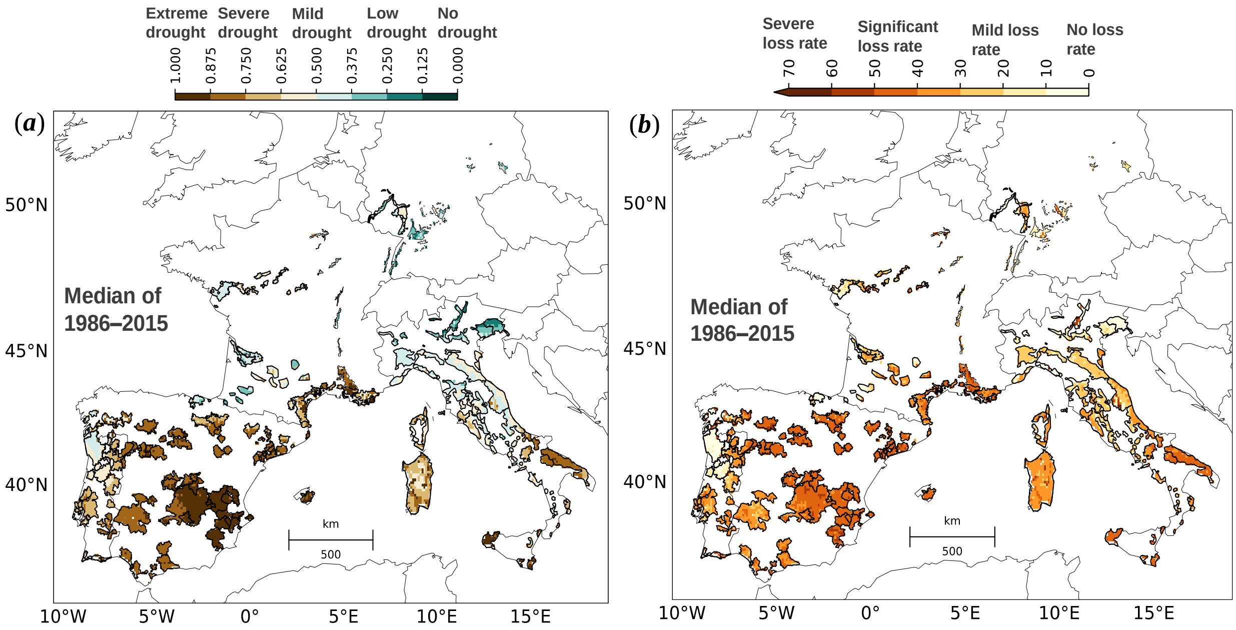

Figure 1. Median values of the (*a*) mean flowering-veraison CWSI and (*b*) potential YLR (%) attributing to the seasonal cumulative water stress over 1986–2015.

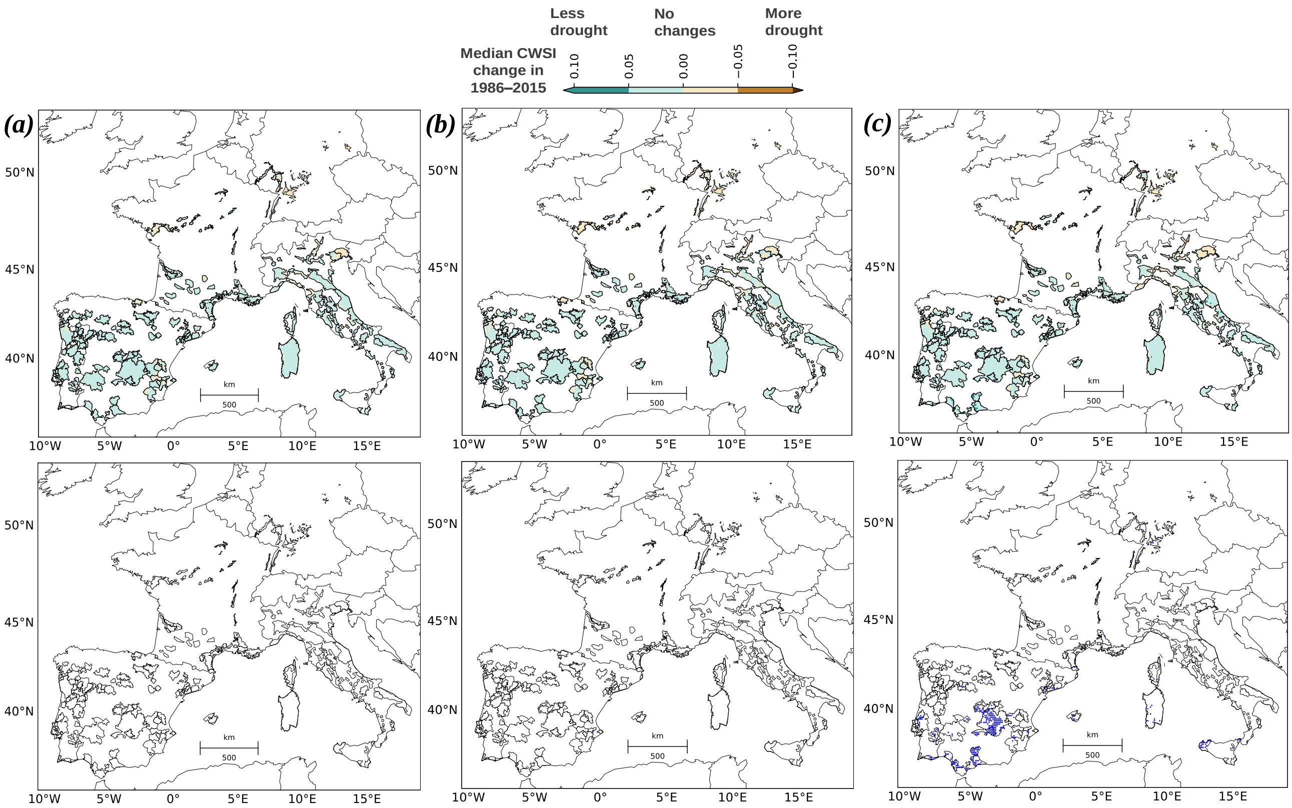

Figure 2. The median changes of the mean crop water stress indicator (CWSI) between the flowering and veraison stage over 1986–2015 by shifting the flowering-veraison phase (*a*) 5% earlier; (*b*) 15% earlier and (*c*) 25% earlier. In the upper panel, absolute change of CWSI is shown. In the lower panel, the Mann-Whitney rank test is performed to check if the median CWSI change over 1986—2015 is significantly different at $p <= 0.05$. Significant grids are marked with blue plus symbols, whereas grids without colours indicate no significance (empty areas).

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