Climate change projections to support the transition to climate-smart viticulture

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Abstract

Climate is a dynamic entity that has been significantly forced by human activities since the pre-industrial era, but mostly in recent decades. Climate change projections hint at shifts in the large-scale atmospheric circulation spatial patterns and temporal regimes, with implications on the weather and climate conditions throughout the planet. These changes will potentially affect, with varied intensity, all environmental and agricultural systems. More specifically, viticulture is not only exposed to changing climates but is also highly vulnerable, as grapevine phenology and physiological development are strongly controlled by atmospheric conditions. Therefore, the assessment of climate change projections for a given region is critical for climate change adaptation and risk reduction in viticulture. By adopting timely and suitable measures, the future sustainability and resiliency of the sector can be fostered. Climate-grapevine chain modelling is an essential tool for better planning and management, supporting day-to-day decisions in vineyards and wineries. Nonetheless, the accuracy of the resulting projections is limited by many uncertainties that must be duly taken into account when transferring knowledge to stakeholders and decision-makers. Climate-smart viticulture should comprise sets of locally tuned strategies, from the short-term to the long-term, envisioning both adaptation and mitigation, assisted by emerging technologies and decision-support systems.

Introduction

The Earth’s system is undergoing major changes through a wide range of spatial and temporal scales as a response to growing anthropogenic radiative forcing, which is pushing the whole system far beyond its natural variability (IPCC, 2021). Sources of greenhouse gases largely exceed their sinks, thus leading to a strengthened greenhouse effect. More energy is thereby being supplied to the system, with inevitable shifts in climatic patterns and weather regimes. Over the last decades, these modifications have been manifested in the full statistical distributions of the atmospheric variables, leading, in some cases, to dramatic changes in the frequency and intensity of weather and climate extreme events (IPCC, 2021). Natural hazards, such as severe droughts, floods, hailstorms, windstorms, forest fires or heatwaves, are being triggered by extreme atmospheric events worldwide, thus threatening natural ecosystems and human activities (IPCC, 2021).

Plants and crops are naturally exposed and vulnerable to climate variability and extremes. In particular, grapevine (*Vitis vinifera* L.) growth and development are known to be strongly connected to atmospheric conditions (Jones, 2007; van Leeuwen & Darriet, 2016; Santos *et al.*, 2020a), namely air temperature and heat accumulation, precipitation and potential evapotranspiration, solar radiation flux and cloudiness, wind speed and gusts, as well as weather extremes (e.g. hail, late frosts, heat waves, windstorms, droughts). Not only yields but also grape berry quality parameters (Costa *et al.*, 2020), wine style and typicity are largely influenced by the weather conditions during a given seasonal cycle, as well as by mesoclimatic and microclimatic characteristics that are a key element of the local *terroir* (van Leeuwen *et al.*, 2004).

Climate change is thereby a major challenge to viticulture and oenology. As such, climate change projections are an essential tool to support the necessary sectoral adaptation. These projections are based on chains of climate models, ranging from Global Climate Models (GCM) to Regional Climate Models (RCM), following a strategy commonly known as model nesting or dynamical downscaling, where simulations/experiments using GCM-RCM chains generate useful climatic information. For this purpose, simulations such as those generated by the EURO-CORDEX project within a European-wide sector can be used (https://dx.doi.org/10.24381/cds.bc91edc3). In addition, a large dataset of regional climate change projections over Europe was collected and bias-adjusted within the framework of the project "Clim4Vitis - Climate change impact mitigation for European viticulture: knowledge transfer for an integrated approach" (https://clim4vitis.eu/), being applied to viticultural research in several recent studies (Reis *et al.*, 2022; Rodrigues *et al.*, 2022; Yang *et al.*, 2022a). Statistical downscaling approaches (Casanueva *et al.*, 2016), e.g., using geostatistical or machine learning methods, may, however, also be a valuable tool to better replicate the observed conditions at narrower scales (Fonseca & Santos, 2018), such as on a vineyard plot. The production of temperature, precipitation or potential evapotranspiration projections, among other variables, for a given wine region is of major relevance for decision-making in viticulture. These projections can be the basis to run grapevine models, ranging from simple bioclimatic indices (Fraga *et al.*, 2019; Santos *et al.*, 2020b) to more complex stochastic or process-based models (Fraga *et al.*, 2016; Leolini *et al.*, 2020). When duly calibrated and validated using local observations, these models may eventually generate outputs directly related to the potential grapevine responses to climate change scenarios and projections, such as in terms of yield, phenology, abiotic stresses (e.g., water, heat or nitrogen), biomass production or grape berry quality indicators, which are adjusted to the regional-to-local features (Fraga *et al.*, 2016; Yang *et al.*, 2022a; Yang *et al.*, 2022b).

Materials and methods

For the production of climate change projections, data from the multi-model ensembles of GCMs of the latest report of the Intergovernmental Panel on Climate Change (IPCC) (i.e., the Sixth Assessment Report, AR6) were selected and retrieved from the IPCC Working Group I (WGI) dataset. Although other higher-resolution datasets are available within specific geographic windows, using the aforementioned dynamical downscaling methodologies, the focus of the present article is on providing examples of worldwide climate change projections that can be used for decision-making in viticulture. GCM datasets are thereby targeted. For this purpose, some global projections are provided based on the newly available experiments and simulations run within the framework of the sixth Climate Model Intercomparison Project, CMIP6 (Eyring *et al.*, 2016). The new Shared Socioeconomic Pathway (SSP) scenarios are used (IPCC, 2021), namely the most common combinations: SSP1-2.6 (sustainability scenario), SSP2-4.5 (intermediate scenario), SSP3-7.0 (regional asymmetric scenario) and SSP5-8.5 (fossil fuel-intensive scenario). The future periods are typically split into near-term (2021–2040), medium-term (2041–2060) and long-term (2081–2100). For viticultural planning, the medium-term period is commonly considered the most adequate, particularly when envisioning the plantation of new climate-smart vineyards. Changes between the medium-term period and baseline are considered, using the "climatic normals' 30-year reference period of 1981–2010 as the baseline. Although the changes in the variables/indices were herein preferred over their absolute values to simplify the analysis, these latter values are also very important for decision-making, as certain optimal ranges in each variable ought to be verified, while some critical thresholds should not be crossed to maintain suitability. All produced maps are global and variables/indices are plotted on a regular grid of 1.0º latitude × 1.0º longitude (grid spacing of approximately 110 km along the meridians). Ensemble means are shown to summarize the central tendency within the multi-model ensemble distribution. However, as previously mentioned, other statistical metrics can be used to complement this metric to assess the inter-model uncertainty, namely medians, quartiles, extreme percentiles and corresponding ranges.

Projections for several variables and indices relevant to viticulture were produced. As an extended abstract, only a very succinct demonstration of viticultural-relevant climatic projections is provided herein. In this article, for the sake of succinctness, only two illustrative indices are presented and discussed: the annual mean number of days with maximum temperature above 35ºC (TX35) and the 6-month Standardised Precipitation Index, SPI-6 (Guttman, 1999). The first index reflects changes in excessive heat stress, which is a major threat to viticulture, while the second index is a manifestation of the changes in dryness conditions and drought severity, which is also a critical aspect for the sustainability of viticulture. TX35 is calculated using gridded daily maximum temperatures simulated by the different GCMs, whereas SPI-6 is based on gridded daily total precipitation. For an accurate computation of extreme indices, such as TX35, a preliminary bias correction is critical to ensure the reliability and accuracy of the projections (Martins *et al.*, 2021). The recently developed ISIMIP3 method (https://www.isimip.org/) is used herein for this goal. These two selected indices are based on the most recent climate models and anthropogenic radiative forcing scenarios, thus reflecting the state-of-the-art of climate change projections. Furthermore, they were chosen from a vast list of strong candidates, including widely known bioclimatic indices of viticultural suitability (e.g., Huglin Heliothermic Index, Riou Dryness Index, Branas Hydrothermal Index, Cool Night Index, Chilling Portions, Biologically Effective Degree Days, amongst many others), or more elaborate indices resulting from grapevine modelling (e.g., phenological timings, yield or abiotic stresses). This choice is aimed at delivering general information that can be easily understood by a less specialized reader.

Results and discussion

The medium-term changes in the TX35 index (extremely warm days) reveal increases throughout the planet, but more dramatic throughout the tropical (low-latitude) areas, like the Amazonas Basin in Southern America. In these regions, current temperatures are already very close to the 35ºC threshold, which implies that even slight warming trends will lead to significant changes in this extreme index (non-linear response). As expected, the changes gradually decrease poleward, with null changes at high latitudes (no occurrence). However, for many wine regions worldwide, a significant increase in TX35 is still noteworthy (e.g., in some areas of the USA, South Africa, Australia or Southern Europe), though a more detailed analysis should be carried out for each region separately and using RCM-downscaled data, as previously referred.

Regarding SPI-6, the pattern is quite different from TX35, depicting both positive and negative anomalies, i.e. wetting and drying trends, respectively. In this case, many important wine regions worldwide will undergo drying trends, particularly those in Southern and Western Europe, Chile, California, South Africa and Australia. Again, these outcomes deserve a much more detailed regional analysis, also taking into account actual evapotranspiration and soil water balance under future climatic conditions (Andrade *et al.*, 2021). Water stress indicators obtained from grapevine dynamical/mechanistic model runs, incorporating local specificities and *terroirs*, are also of high relevance for an accurate assessment of the potential impacts of these projections in the vineyards of each wine region, namely when taking into account the most sensitive periods of grapevine growing cycle (Yang *et al.*, 2022a).

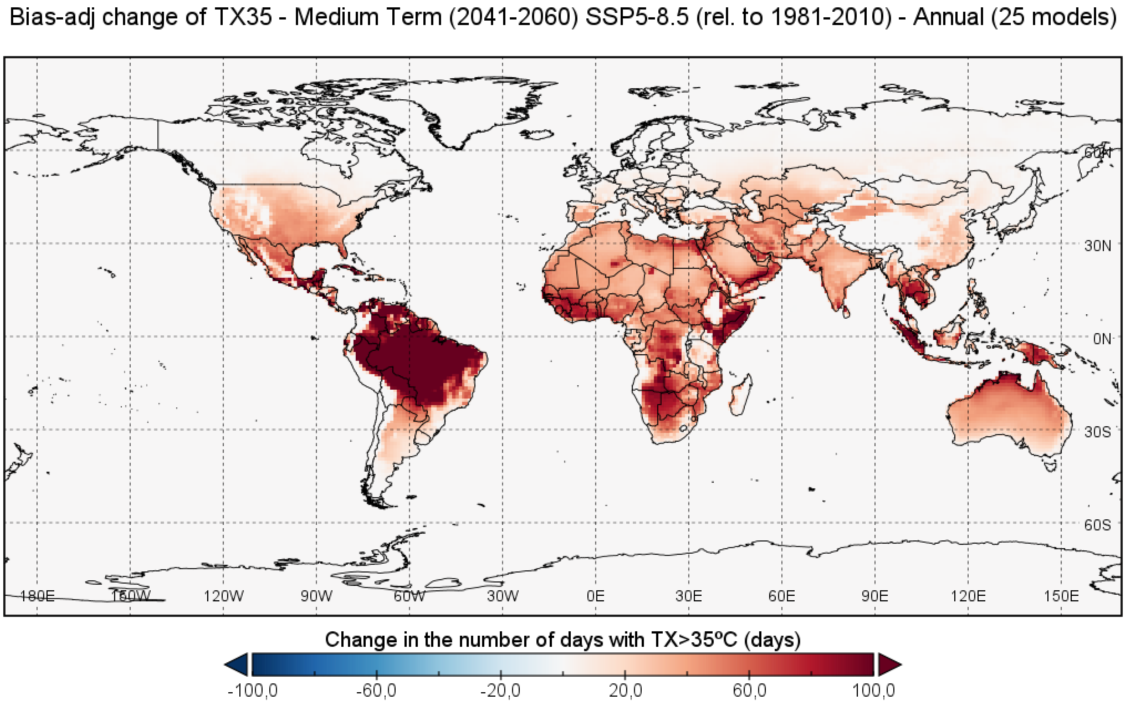

Figure 1. Ensemble-mean change in the annual number of days with maximum temperature (TX) above 35ºC (in days) for the medium-term period (2041-2060) with respect to the baseline period of 1981-2010. The ensemble comprises 25 Global Climate Models. Data was bias-adjusted using the ISIMIP3 method.

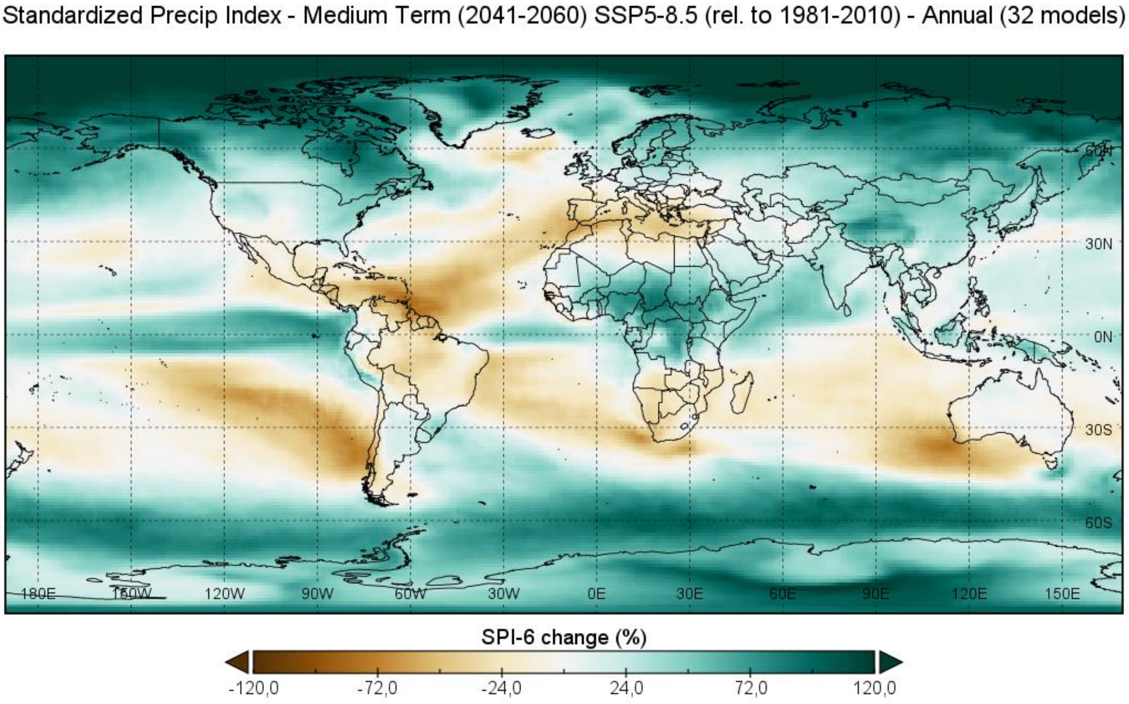

Figure 2. Ensemble-mean relative change in the 6-month Standardised Precipitation Index (SPI-6, in %) for the medium-term period (2041-2060) with respect to the baseline period of 1981-2010. The ensemble comprises 32 Global Climate Models.

Despite the general information withdrawn from the previous global patterns, projections of grapevine responses at the vineyard scale are of foremost importance to the winemaking sector, as they are the ground to identify the best suite of adaptation options for a given location/vineyard, but can also be used to plan new vineyard areas or, in more extreme situations, to abandon areas with future low suitability, thus reshaping the wine region’s boundaries. A wide range of adaptation options does exist in viticulture, thus providing a reasonable adaptation potential and plasticity to climate change. Adaptation strategies can vary from short-term (within one or two vintages) to long-term measures (decades), though their boundaries are not always clear (Santos *et al.*, 2020a). Supplemental irrigation has been mentioned as one of the most important adaptation measures, particularly under Mediterranean-type or sub-arid/arid climates. Nevertheless, water resources are frequently scarce in these same regions and viticulture needs to compete with more powerful sectors, like domestic water consumption or hydropower production. Therefore, the sustainability of this practice is strongly constrained. More efficient water management, accompanied by wastewater treatment and reuse, may represent alternative solutions but are very likely to be insufficient to cope with changing climates, partially because of other emerging biotic and abiotic factors, such as new pests and diseases or strengthened heat stress. On the other hand, an irrigated vineyard tends to be less drought-resistant, which may exacerbate grapevine water consumption and dependency, reducing the overall water use efficiency and sustainability. Other strategies can also bring significant adaptation potentials, such as adapted canopy management, application of sunscreen materials or shading, soil management, or pest and disease control. All these strategies can be combined and adjusted in different ways according to the *terroirs* and regional-to-local climate change projections. Moreover, when planning new vineyards for a given area, long-term options are also available, such as the adoption of adequate training systems, scion-rootstock combination selection, or varietal and clonal selection. The microclimatic selection through vineyard relocation may also be a very effective measure. By planting new vineyards in cooler areas, e.g., at higher elevations or with lower solar exposure, at higher latitudes or closer to the coastline, it is possible to offset, at least partially, the projected detrimental warming and/or drying trends.

The winemaking sector can also reduce the carbon footprint through the adoption of carbon sequestration strategies in the vineyards (climate change mitigation measures). Better soil management and soil health promotion, waste treatment and reuse, circular economy and valorization of co-products, and more efficient energy consumption, amongst others, can play a key role in achieving this goal. Despite some possible conflicts between adaptation and mitigation measures, in many circumstances, they can act synergetically and contribute to the transition to climate-smart viticulture. The implementation of suitable and cost-effective, but also timely and go-green adaptation measures will decisively contribute to the socio-economic and environmental sustainability of the entire wine value chain.

Conclusion

The potential impacts of changing climates and the corresponding risks for the sustainability of the viticulture and winemaking sector in each region are not homogeneous. Even though an overall warming trend is projected virtually everywhere, different wine regions may experience very diverse climate change signals in multifaceted ways (e.g., either drying or wetting trends). Furthermore, depending on the intensity and timescale of the changes, the challenges to the winemaking sector may rely on different strategies to maintain the sustainability of the sector. Therefore, the transition to climate-smart viticulture will have to encompass locally tuned strategies, ranging from the short-term to the long-term applicability, also promoting both climate change adaptation and mitigation. The application and/or development of cutting-edge techniques and technologies, as well as the development of viticulture-customized decision-support systems, are key tools for this already ongoing transition.

References

Andrade, C., Contente, J., & Santos, J. A. (2021). Climate Change Projections of Aridity Conditions in the Iberian Peninsula. *Water*, *13*(15), 2035. Retrieved from https://www.mdpi.com/2073-4441/13/15/2035

Casanueva, A., Herrera, S., Fernández, J., & Gutiérrez, J. M. (2016). Towards a fair comparison of statistical and dynamical downscaling in the framework of the EURO-CORDEX initiative. *Climatic Change*, *137*(3), 411-426. https://doi.org/10.1007/s10584-016-1683-4

Costa, C., Graça, A., Fontes, N., Teixeira, M., Gerós, H., & Santos, J. A. (2020). The Interplay between Atmospheric Conditions and Grape Berry Quality Parameters in Portugal. *Applied Sciences, 10*(14), 4943. Retrieved from https://www.mdpi.com/2076-3417/10/14/4943

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.*, *9*(5), 1937-1958. https://doi.org/10.5194/gmd-9-1937-2016

Fonseca, A. R., & Santos, J. A. (2018). High-Resolution Temperature Datasets in Portugal from a Geostatistical Approach: Variability and Extremes. *Journal of Applied Meteorology and Climatology*, *57*(3), 627-644. https://doi.org/10.1175/Jamc-D-17-0215.1

Fraga, H., García de Cortázar Atauri, I., Malheiro, A. C., & Santos, J. A. (2016). Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Global Change Biology*, *22*(11), doi:10.1111/gcb.13382. https://doi.org/10.1111/gcb.13382

Fraga, H., Pinto, J. G., & Santos, J. A. (2019). Climate change projections for chilling and heat forcing conditions in European vineyards and olive orchards: a multi-model assessment. *Climatic Change*, *152*(1), 179-193. https://doi.org/10.1007/s10584-018-2337-5

Guttman, N. B. (1999). Accepting the Standardized Precipitation Index: a calculation algorithm. *Journal of the American Water Resources Association*, *35*(2), 311-322. https://doi.org/10.1111/j.1752-1688.1999.tb03592.x

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S.L., Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R., Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou Ed. Vol. 1). New York, USA: IPCC.

Jones, G. (2007). Climate Change: Observations, Projections, and General Implications for Viticulture and Wine Production. *Practical Winery and Viticulture*, *29*.

Leolini, L., Costafreda-Aumedes, S., A. Santos, J., Menz, C., Fraga, H., Molitor, D., Merante, P., Junk, J., Kartschall, T., Destrac-Irvine, A., van Leeuwen, C., C. Malheiro, A., Eiras-Dias, J., Silvestre, J., Dibari, C., Bindi, M., & Moriondo, M. (2020). Phenological Model Intercomparison for Estimating Grapevine Budbreak Date (Vitis vinifera L.) in Europe. *Applied Sciences*, *10*(11), 3800. Retrieved from https://www.mdpi.com/2076-3417/10/11/3800

Martins, J., Fraga, H., Fonseca, A., & Santos, J. A. (2021). Climate Projections for Precipitation and Temperature Indicators in the Douro Wine Region: The Importance of Bias Correction. *Agronomy, 11*(5), 990. Retrieved from https://www.mdpi.com/2073-4395/11/5/990

Reis, S., Martins, J., Gonçalves, F., Carlos, C., & Santos, J. A. (2022). European Grapevine Moth and Vitis vinifera L. Phenology in the Douro Region: (A)synchrony and Climate Scenarios. *Agronomy, 12*(1), 98. Retrieved from https://www.mdpi.com/2073-4395/12/1/98

Rodrigues, P., Pedroso, V., Reis, S., Yang, C., & Santos, J. A. (2022). Climate change impacts on phenology and ripening of cv. Touriga Nacional in the Dão wine region, Portugal. *International Journal of Climatology, n/a*(n/a). https://doi.org/https://doi.org/10.1002/joc.7633

Santos, J. A., Fraga, H., Malheiro, A. C., Moutinho-Pereira, J., Dinis, L. T., Correia, C., Moriondo, M., Leolini, L., Dibari, C., Costafreda-Aumedes, S., Kartschall, T., Menz, C., Molitor, D., Junk, J., Beyer, M., & Schultz, H. R. (2020a). A Review of the Potential Climate Change Impacts and Adaptation Options for European Viticulture. *Applied Sciences-Basel, 10*(9). https://doi.org/10.3390/app10093092

Santos, M., Fonseca, A., Fraga, H., Jones, G. V., & Santos, J. A. (2020b). Bioclimatic conditions of the Portuguese wine denominations of origin under changing climates. *International Journal of Climatology, 40*(2), 927-941. https://doi.org/https://doi.org/10.1002/joc.6248

van Leeuwen, C., & Darriet, P. (2016). The Impact of Climate Change on Viticulture and Wine Quality. *Journal of Wine Economics, 11*(1), 150-167. https://doi.org/10.1017/jwe.2015.21

van Leeuwen, C., Friant, P., Chone, X., Tregoat, O., Koundouras, S., & Dubourdieu, D. (2004). Influence of climate, soil, and cultivar on terroir. *American Journal of Enology and Viticulture, 55*(3), 207-217.

Yang, C., Menz, C., De Abreu Jaffe, M. S., Costafreda-Aumedes, S., Moriondo, M., Leolini, L., Torres-Matallana, A., Molitor, D., Junk, J., Fraga, H., van Leeuwen, C., & Santos, J. A. (2022a). Projections of Climate Change Impacts on Flowering-Veraison Water Deficits for Riesling and Müller-Thurgau in Germany. *Remote Sensing, 14*(6), 1519. Retrieved from https://www.mdpi.com/2072-4292/14/6/1519

Yang, C., Menz, C., Fraga, H., Costafreda-Aumedes, S., Leolini, L., Ramos, M. C., Molitor, D., van Leeuwen, C., & Santos, J. A. (2022b). Assessing the grapevine crop water stress indicator over the flowering-veraison phase and the potential yield lose rate in important European wine regions. *Agricultural Water Management, 261*, 107349. https://doi.org/https://doi.org/10.1016/j.agwat.2021.107349