

EXTENDED ABSTRACT

Climate regionalization of Uruguayan viticulture for ecological sustainability

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ABSTRACT

Context and purpose of the study. Over the last three decades, climate change in Uruguay has intensified, potentially reshaping the country's viticultural climate zoning. In this context, a climate classification for viticulture based on data from 1961 – 1990 was updated so as to capture the spatio-temporal variability of the climate and to help the wine sector anticipate the challenges arising from climate change. This study seeks to refresh the climatic regionalisation of Uruguay for viticulture based on data from the 1994 – 2023 period in order to compare with the historical classification.

Materials and methods. Using daily observations from 17 quality-controlled meteorological stations (1993 – 2024), we computed and mapped a suite of indicators for viticulture at a 1-km resolution over Uruguay: the Huglin index, Cool-Night Index, seasonal rainfall amount, Chilling Hours and grapevine phenological indices (GFV and GSR). Spatialisation combines a multiple-linear regression (with elevation, distance to the sea, latitude, longitude as predictors) and inverse-distance weighting of the residuals. The resulting maps were compared with the historical classification to assess climate change, whereas

two contrasted years highlighted the interannual variability due to the large-scale El Niño Southern Oscillation — 2023 (La Niña) and 2024 (El Niño).

Results. The updated viticultural zoning (1994 – 2023) shows a marked warming relative to the previous reference period (1961-1990), with a shift towards upper levels within bioclimatic classes or warmer bioclimatic classes and higher night-time temperatures during ripening. The analysis of seasonal rainfall displays a pronounced decreasing north-south gradient, while accumulated chill hours point to a decline in winter cold. Phenological indices reveal a significant difference between the north (earlier growth cycle) and the south-east (later cycle). The two climate-contrasted years of 2023 (dry and hot conditions) and 2024 (wet conditions) illustrate the magnitude of inter-annual climatic variability. Maritime influence emerges as a potential lever for adaptation, and appropriate strategies (varietal selection, vineyard training systems, water management) should be considered to ensure the long-term sustainability of Uruguayan viticulture in the context of global warming.

INTRODUCTION

Climate change, characterised by a global rise in temperature and a higher frequency of extreme events, is significantly affecting many eco agro-systems, including viticulture (Barbeau et al., 2015; Jones et al., 2005). Over recent decades, various wine-growing regions have documented earlier phenological stages, higher grape sugar concentrations and, in some cases, lower acidity (Ollat et al., 2016). To describe and anticipate these effects, a range of climatic classifications for viticulture has been developed—from heat-sum indices (Huglin, 1978; Winkler, 1974) to multi-criteria approaches that incorporate e.g. heat, dryness and night-time coolness (Tonietto & Carbonneau, 2004).

Against this backdrop, Uruguay—lying at mid-latitudes (~30–35° S) and flanked to the South by the Río de la Plata estuary and to the East by the Atlantic Ocean—experiences particularly variable climate conditions (Ferrer, 2007). Several studies highlighted both maritime influence and meso-climatic variability within the Uruguayan vineyard,

which together amplify year-to-year heterogeneity in ripening conditions (Fourment et al., 2014, 2024; Tachini et al., 2023). At the national scale (Fig. 1a), a first viticultural regionalisation was proposed by Milka Ferrer (2007) using the 1961–1990 climatic norm. During the past three decades, the global warming trend reported by the IPCC (2021) has also been evident in Uruguay, altering thermal and rainfall conditions relative to the 1961–1990 baseline. Newly available data series and methodological approaches (phenological indices, spatial-interpolation methods) now make it possible to update this existing mapping. In addition, recent phenological models have been developed such as GFV (Grapevine Flowering Veraison) and GSR (Grapevine Sugar Ripeness) models (Parker et al., 2011, 2020), which link key phenological stages to accumulated heat.

In this study, we aim to update the climatic regionalisation of Uruguayan viticulture using the 1994–2023 period and

to compare these new maps with the 1961-1990 historical reference of Ferrer (2007). We emphasise on spatial contrasts (north-south gradient, Atlantic influence, etc.) and inter-annual variability (e.g. La Niña versus El Niño

years) in order to better understand how these climatic shifts affect the ecological sustainability of the vineyard (varietal choice, training systems, and other management decisions).

MATERIALS AND METHODS

Daily climate data—minimum (TN), maximum (TX) and mean (TM) air temperatures, together with precipitation—from 17 INUMET (Instituto Nacional de Meteorología) stations were used after quality screening (Fig. 1b). Retention criteria were: (i) less than 5 % missing values per growing season (1 September – 15 March) and/or per index-calculation period, and (ii) at least 22 valid seasons between 1993 and 2024 (19 for precipitation). Should one to three consecutive days of data were missing, the gaps were infilled by interpolation or duplication following the methodology of Verdugo-Vásquez et al. (2023). Data from the INIA (Instituto Nacional de Investigación Agropecuaria) stations were excluded (Fig. 1b) due to systematic offsets exceeding 5 °C relative to those of certain INUMET stations.

From these series we calculated:

1. **Huglin Index (HI)** (Huglin, 1978): from 1 September to 28 February, with coefficient $k = 1$ for Uruguay.
2. **Growing Degrees-Days (GDD)** (Winkler, 1974) : Cumulative $TM > 10$ °C from 1 October to 30 April.
3. **Cool-Night Index (CNI)** (Tonietto & Carbonneau, 2004): TN averaged over the 15 February to 15 March period.
4. **Seasonal precipitation (Pmm)**: rainfall amount from 1 September to 15 March.

RESULTS AND DISCUSSION

Thirty-year period 1994 – 2023

The interpolated climatic maps (Fig. 2) confirm, relative to 1961 – 1990, a significant warming trend and a spatial reorganisation of Uruguay's viticultural climate zoning.

The Huglin Index (HI) (Fig. 2a) now averages 2374 ± 174 units, ranging from ~ 1878 to > 2830 . According to the Tonietto & Carbonneau (2004) scale, 7 % of the country falls in the HI3 class (1800 – 2100), 49 % in the HI4 class (2100 – 2400) and 44 % in the HI5 class (2400 – 3000). Formerly, the southern littoral oscillated between the HI3 and HI4 classes and the north-west between the HI4 and HI5 classes. As a result of warming, they shift towards the upper level of each class with accentuated latitudinal gradient—the north falls now entirely into the IH5 warm class), whereas the south-east littoral, moderated by the estuary and the Atlantic, still remains into the cooler class (IH3).

Cool-Night Index (CNI) (Fig. 2b) averages 17.2 °C ± 0.55 ; almost the whole country (91 %) falls into the CNI2 class (14–18 °C) and 9 % into the warmest CNI class (> 18 °C). The emergence of hot nights (CNI1)—non-existent in the 1961–1990 regionalisation—reflects the rise in minimum temperatures already noted by Fourment Reissig (2016). The north-south contrast remains pronounced, with the coastal fringe generally staying within CNI2.

5. Chill Hours (CH): Hours ≤ 7 °C accumulated between 1 May and 31 August, using the daily method of Linvill (1990), reconstructing a two-phase temperature curve (daytime rise, night-time decline) from daily TN and TX.

6. Phenological indices (GFV, GSR) (Parker et al., 2011 ; 2020) : Theoretical dates of flowering and sugar ripeness for various cultivars, obtained by summing TM (base 0 °C) as from 1 September (GFV) or 1 October (GSR) until the heat requirement of the specific cultivar is met.

We produced high 1-km-resolution maps of each index over Uruguay for the 30-year period 1994–2023. To highlight inter-annual variability, we also analysed two climate contrasted consecutive years: 2023 , hot and dry conditions under La Niña circulation, and 2024, wet conditions under El Niño circulation. Spatial interpolation combines a multiple regression (index versus elevation, distance to the sea, latitude, longitude) as described in Amiot et al. (2023), to which inverse-distance weighting of the residuals was added. This cross-validated approach captures the north-south gradients and maritime influence and facilitates comparison with the results of Ferrer (2007).

Rainfall during the growing season (September–March) (Fig. 2c) averages 751 mm ± 73 , showing a significant north-south gradient for viticulture (≈ 600 mm in the south, ≈ 900 mm in the north) and an eastward increase linked to the Atlantic façade.

The accumulated winter Chill Hours (CH) (Fig. 2d)—estimated at 493 h ± 67 below 7 °C between 1 May and 31 August—also displays a north-south gradient: the warmer north records fewer cold hours than the south, which could ultimately affect winter phenology (Londo & Johnson, 2014).

Finally, the GFV and GSR indices for the *Tannat* cultivar (Fig. 2e–f) reveal a difference in phenological offset of roughly 2–3 weeks between the north (earlier cycle) and the south-east (later). Flowering dates range from mid-November (north) to late November (south), while the date at which the heat requirement to reach 200 g L⁻¹ sugar maturity varies from mid-February (north) to early March (south-east). Although these phenological indices were not previously mapped, their present distributions corroborate the vine's thermal sensitivity (Parker et al., 2020) and the cooling influence of the Atlantic (Tachini et al., 2023).

Inter-annual variability: comparison between 2023 (La Niña) and 2024 (El Niño)

To illustrate inter-annual climate variability and the importance of the impact of the ENSO circulation, Figure 3 juxtaposes two indices—HI and precipitation—under opposite ENSO phases. In 2023 (La Niña), the Huglin Index rose to 2543 ± 183 u, while rainfall was below normal, aggravating water stress. The share of the territory in the hottest class IH5 (> 2400 u) therefore climbed to 80 %, compared with 44 % for the 30-year mean. Conversely, El Niño conditions

led to more moderate HI (2301 ± 171 u) and greater rainfall amounts, reducing drought risk, yet triggering other hazards (e.g. fungal diseases). This comparison demonstrates the possible amplitude of annual fluctuations and underlines the need to adjust vineyard management—water use, pest and diseases management—to climatic conditions that can deviate markedly from the underlying warming trend.

Synthesis of results

This agro-climatic mapping for the 1994 – 2023 period highlights an intensified north–south thermal gradient and the expansion of the warmest classes (IH4–IH5, IF1) in Uruguay relative to that of 1961 – 1990. Despite broadly stable annual rainfall amounts (600–900 mm), inter-annual variability—especially under ENSO influence—remains substantial. The cumulative hours ≤ 7 °C indicate a moderate decline in winter chill, while the phenological indices (GFV, GSR) reveal a two- to three-week offset between earlier northern sites and later south-eastern ones.

The mapping also highlights the cooling effect of Atlantic proximity—already noted by Fourment et al. (2014), which emerges as a key resilience lever for the emerging south-eastern vineyards, as shown in other countries such as in South Africa (Bonnardot et al., 2002).

Finally and methodologically, the country's low relief and sparse station network introduce some interpolation uncertainty, although the multiple-regression + IDW approach mitigates part of these biases.

CONCLUSION

These findings confirm both significant warming, strong latitudinal contrasts and high year-to-year climate variability that represents important challenges to which winegrowers need to adapt. In that sense, appropriate adaptation strategies, such as varietal selection, yield and canopy management, pests and diseases control, and water management, should be considered to ensure the long-term sustainability of Uruguayan viticulture in the context of global warming.

Further climate studies will consider both long-term and regional scales including i) analyses of future climate conditions using the CMIP6 simulations and the Shared Socioeconomic Pathways (SSP scenarios) as defined in IPCC (2021), ii) analysis of ENSO impacts on Uruguayan viticulture and iii) analysis of the seabreeze impacts on coastal vineyards in order to help winegrowers in their decision-making.

REFERENCES

- Amiot, L., Dubreuil, V., & Bonnardot, V. (2023). Le changement climatique en Bretagne : Cartographie sur la période observée (1951-2020) et future (2031-2100). *Noréis*, 266(1), 7-25. <https://doi.org/10.3917/nor.266.0007>
- Barbeau, G., Neethling, E., Ollat, N., Quénel, H., & Touzard, J.-M. (2015). Adaptation au changement climatique en agronomie viticole. *Agronomie, Environnement & Sociétés*, 5(1), 67-75.
- Bonnardot, V., Planchon, O., Carey, V., Cautenet, S. (2002). Diurnal wind, relative humidity and temperature Variation in the Stellenbosch-Groot Drakenstein wine growing area. *S. Afr. J. Enol. Vitic*, 23(2), 62-71.
- Ferrer, M. (2007). Étude du climat des régions viticoles de l'Uruguay, des variations climatiques et de l'interaction apportée par le microclimat et l'écophysiologie des systèmes de conduite Espalier et Lyre sur Merlot [These de doctorat, Montpellier, ENSA]. <https://theses.fr/2007ENSA0033>
- Fourment, M., Bonnardot, V., Planchon, O., Ferrer, M., & Quénel, H. (2014). Circulation atmosphérique locale et impacts thermiques dans un vignoble côtier : Observations dans le sud de l'Uruguay. *Climatologie*, 11, 47-64. <https://doi.org/10.4267/2042/56254>
- Fourment, M., Tachini, R., Bonnardot, V., & Collins, C. (2024). Assessment of Albariño (*Vitis vinifera* sp.) plasticity to local climate in the Atlantic eastern coastal terroir of Uruguay : *OENO One*, 58(4), Article 4. <https://doi.org/10.20870/oeno-one.2024.58.4.8196>
- Fourment Reissig, M. M. (2016). *Adaptation de la vigne (Vitis vinifera L.) à la variabilité de la température à méso-échelle en Uruguay* (Numéro 2016REN20026) [Theses, Université Rennes 2 ; Universidad de la República (Montevideo)]. <https://theses.hal.science/tel-01380090>
- Huglin, P. (1978). Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole [climatologie]. *Comptes Rendus Des Séances de l'Académie d'Agriculture de France*, 64. <https://agris.fao.org/search/en/providers/123819/records/64735ac608fd68d546024e94>
- Intergovernmental Panel on Climate Change (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, et al., Éd.). Cambridge University Press. <https://doi.org/10.1017/9781009157896>
- Jones, G. V., White, M. A., Cooper, O. R., & Storchmann, K. (2005). Climate Change and Global Wine Quality. *Climatic Change*, 73(3), 319-343. <https://doi.org/10.1007/s10584-005-4704-2>
- Londo, J. P., & Johnson, L. M. (2014). Variation in the chilling requirement and budburst rate of wild Vitis species. *Environmental and Experimental Botany*, 106, 138-147. <https://doi.org/10.1016/j.envexpbot.2013.12.012>

Ollat, N., Touzard, J.-M., & Leeuwen, C. van. (2016). Climate Change Impacts and Adaptations : New Challenges for the Wine Industry. *Journal of Wine Economics*, 11(1), 139-149. <https://doi.org/10.1017/jwe.2016.3>

Parker, A., Cortázar-Atauri, I. G. de, Trought, M. C. T., Destrac, A., Agnew, R., Sturman, A., & Leeuwen, C. van. (2020). Adaptation to climate change by determining grapevine cultivar differences using temperature-based phenology models *OENO One*, 54(4), Article 4. <https://doi.org/10.20870/oeno-one.2020.54.4.3861>

Parker, A., De Cortázar-Atauri, I. g., Van Leeuwen, C., & Chuine, I. (2011). General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. *Australian Journal of Grape and Wine Research*, 17(2), 206-216. <https://doi.org/10.1111/j.1755-0238.2011.00140.x>

Tachini, R., Bonnardot, V., Ferrer, M., & Fourment, M. (2023). Topography interactions with the Atlantic Ocean and its impact on *Vitis vinifera* L. « Tannat ». *VITIS - Journal of Grapevine Research*, 163-177 Pages. <https://doi.org/10.5073/VITIS.2023.62.163-177>

Tonietto, J., & Carboneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and Forest Meteorology*, 124(1), 81-97. <https://doi.org/10.1016/j.agrformet.2003.06.001>

Verdugo-Vásquez, N., Orrego, R., Gutiérrez-Gamboa, G., Reyes, M., Silva, A. Z., Balbontín, C., Gaete, N., & Salazar-Parra, C. (2023). Climate trends and variability in the Chilean viticultural production zones during 1985–2015. *OENO One*, 57(1), Article 1. <https://doi.org/10.20870/oeno-one.2023.57.1.7151>

Winkler, A. J. (1974). *General Viticulture : Second Revised Edition*. University of California Press.

FIGURES

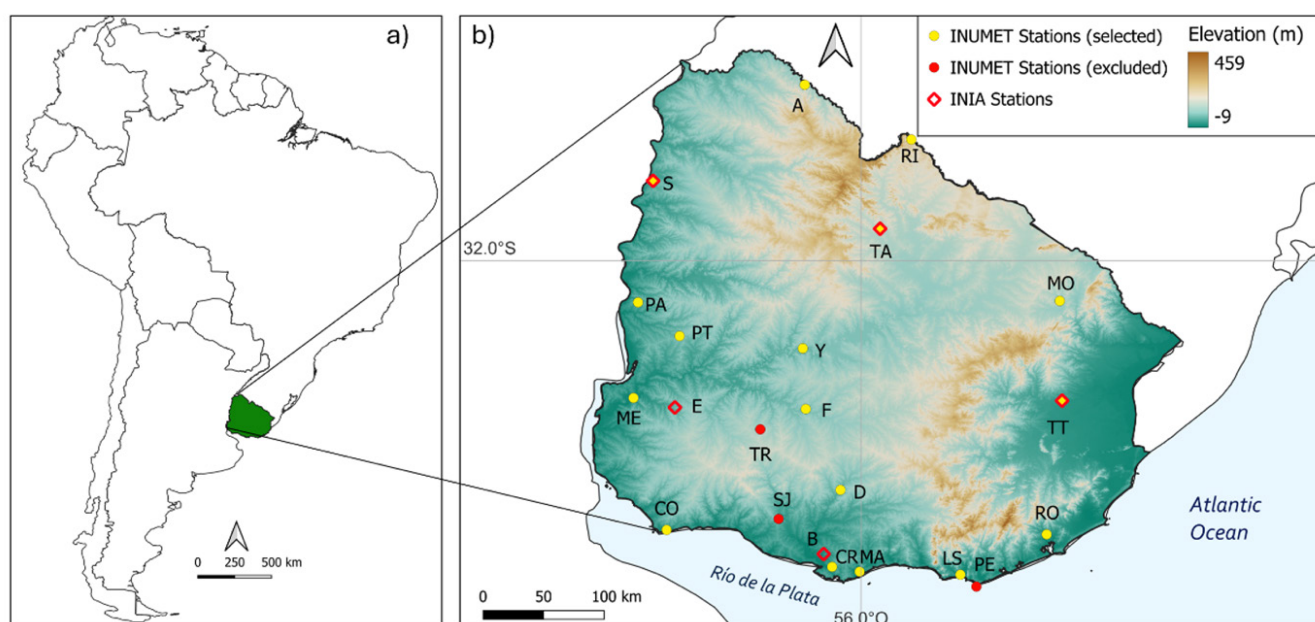


Figure 1. Location of Uruguay (a) and of the weather stations (b). The 17 INUMET stations retained for the study are shown as yellow circles, the 3 INUMET stations not retained as red circles, and the 5 INIA stations as red diamonds.

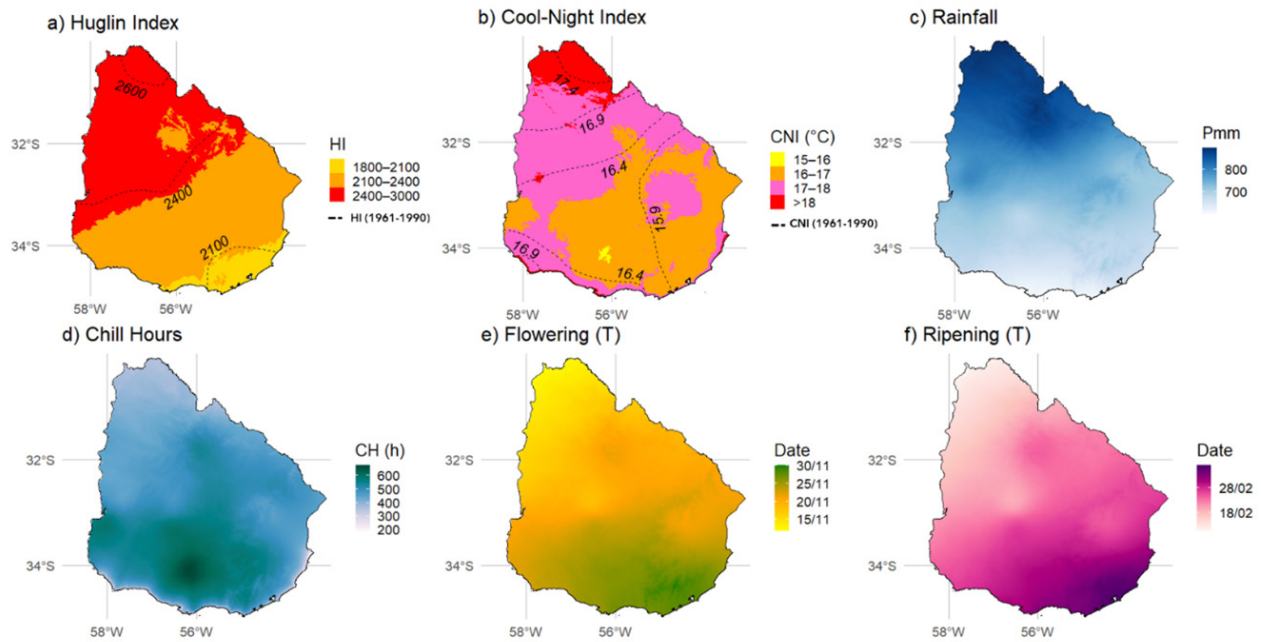


Figure 2. Climatic and phenological indices for the 1994 – 2023 period (1-km interpolated spatial means). a) Huglin Index (HI); b) Cool-Night Index (CNI, °C); c) Seasonal precipitation total (mm): sum from 1 Sept. to 15 Mar.; d) Accumulated Chill Hours (CH, hours ≤ 7 °C); e) Theoretical flowering date of Tannat (GFV); f) Theoretical date at 200 g L⁻¹ sugar target (GSR) for Tannat.

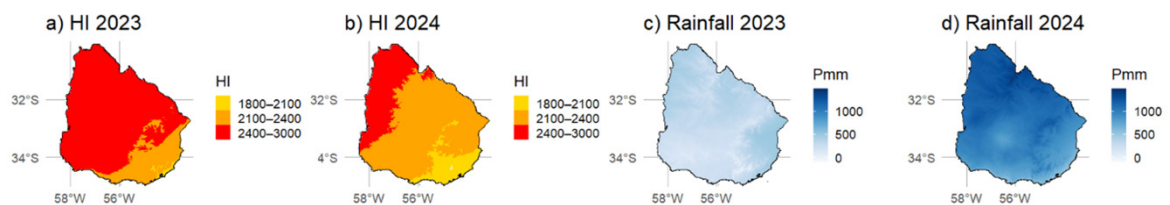


Figure 3. Huglin Index (HI) in a) 2023 and b) 2024 ; Gowing-season rainfall (mm) in c) 2023 and d) 2024.