Maria Zavlyanova[1], Valérie Bonnardot ([2*]), Cornelis van Leeuwen[1, 3], Hervé Quénol[2], Nathalie Ollat[1,3]

The use of GFV and GSR temperature-based models in emerging wine regions to help decision-making regarding choices in grape varieties and wine styles. Application to Brittany (France)

Affiliation
[1]Bordeaux Sciences Agro, Gradignan, France
[2]LETG-Rennes UMR 6554 CNRS, Université Rennes 2, Rennes, France
[3]EGFV, Univ. Bordeaux, Bordeaux Sciences Agro, INRAE, ISVV, Villenave d'Ornon, France

Correspondence
Maria Zavlyanova: maria.zavlyanova@outlook.com, Valérie Bonnardot*: valerie.bonnardot@univ-rennes2.fr, Cornelis van Leeuwen: vanleeuwen@agro-bordeaux.fr, Hervé Quénol, herve.quenol@univ-rennes2.fr, Nathalie Ollat: nathalie.ollat@inrae.fr

Summary

Viticulture and wine production are facing climate change. While it can be a challenge in some regions, it is an opportunity for others. The aim of this study is to develop a methodology to assess climatic characteristics and potential for viticulture of new areas, through spatial analyses of data from temperature-based grapevine models (the Grapevine Flowering Veraison model -GFV and the Grapevine Sugar Ripeness model -GSR) during current and future periods. A deadline for veraison was set on the 1st of September for dry wine and on the 15th of September for sparkling wine. Different sugar levels were targeted for the production of different wine styles (170 $g \cdot L^{-1}$ for sparkling wine, 190 $g \cdot L^{-1}$ and 200 $g \cdot L^{-1}$ dry white and red wines, respectively) on the 15th of October. The methodology was applied over the region of Brittany (France) to assess the potential to produce different wine styles from 6 grapevine varieties ('Sauvignon blanc', 'Chardonnay', 'Chenin', 'Pinot noir', 'Cabernet franc' and 'Cabernet-Sauvignon'). Observed data from the Météo-France weather stations network and an 8-km gridded climate model data from the 2014 EUROCORDEX simulation set (CNRM-CM5/RCA4 climate model) were used over the past (1950-2020) and future periods (2031-2060 and 2071-2100) under two GHG emission scenarios (RCP 4.5 and 8.5). Climatic conditions of this region seem to be increasingly suitable in the future depending on climate scenario, time period projections and targeted types of wine. The methodology can be applied to any emerging winegrowing region with the ability to adjust variety choices, time lines and sugar levels thresholds as desired to meet the needs of a specific region.

Keywords

climate change, grapevine variety, veraison, ripeness, temperature-based models, spatialization, Brittany

Introduction

Viticulture and winemaking are going through multiple technical and socio-economical changes inducing permanent evolutions. Climate change, including increasing temperatures, but also climatic hazards such as droughts, frost events (IPCC, 2021), is a particular challenging issue for grape growing, as it is in agriculture in general. Advanced grapevine phenology and modification of grape berry composition (increased sugar content, decreased acidity) are observed throughout the world since the end of the 1980's (Neethling *et al.* 2012, Garcia de Cortázar Atauri *et al.* 2017, van Leeuwen *et al.* 2019). The climate projections and their potential impacts on viticulture in Europe and worldwide (Jones *et al.* 2005, Webb *et al.* 2007 and 2008, Fraga *et al.*, 2013, Hannah *et al.* 2013, Cardell *et al.* 2019, Cabré and Nunez, 2020) urge winegrowers to adapt in order to maintain wine quality and economic sustainability (Duchêne *et al.* 2010, Garcia de Cortázar Atauri *et al.* 2016, Ollat *et al.*, 2016).

In addition to changes in grapevine phenology, yield, wine composition and quality, future climate change impacts on global viticulture also include a geographical redistribution of vineyards. A shift of the suitability of grapevine cultivation to higher latitudes was clearly projected in numerous studies (Malheiro *et al.* 2010, Hannah *et al.* 2013, Moriondo *et al.* 2013, Santos *et al.* 2012, Fraga *et al.*, 2016, Dunn *et al.* 2019, Remenyi *et al.* 2020), up to latitudes as high as those of Scotland or Scandinavia in the northern hemisphere, triggering curiosity for further local investigations. In the meantime, global warming, among other factors, has encouraged the development of wine producing companies in regions located at latitudes higher than 50°N in Europe, such as England and Wales (Spellman 1999, Clout 2013). These regions become increasingly suitable for wine production, and a 250 % growth rate of areas under vines was recorded between 2004 and 2017, while sparkling wine dominates the production (Nesbitt *et al.* 2016, 2018, 2019). It can also be noted that small com-

Submitted/accepted for publication: January 14, 2022/December 9, 2022

panies develop further north, such as in Denmark (Bentzen and Smith 2009) and Sweden, where studies on grapevine growing potential were recently undertaken (Rauhut Kompaniets and Nilson, 2020, Cepnioglu 2021).

Given future climate projections displaying opportunities for new wine regions to develop, as well as the fact that wine is already made in regions situated at latitudes higher than 50°N in Europe, the development of viticulture seems to be conceivable in new French regions, notably in Brittany. A shift to higher latitudes is one of the scenarios for adaptation to climate change being considered by the French wine producing sector. Four adaptation strategies emerged from a prospective study with stakeholders in the wine producing sector who were consulted on their perception of climate change and willingness for adaptation: a "*Conservative scenario*" with little or no change compared to current conditions; an "*Innovative scenario*" with introduction of innovations in order to maintain the vineyard in current geographical areas; a "*Nomadic" scenario*" considering a geographical redistribution of winegrowing region and a "*Liberal scenario*" with less regulation (Aigrain *et al.* 2019). The "*nomadic*" scenario was largely rejected by the wine producing sector, with 3 % of the survey respondents only answering they would act to help implementation of this possible future, fearing loss of terroirs, landscapes and wine typicity (Aigrain *et al.* 2019). However, new vineyards are currently being planted in the north and north-west of France, such as in Brittany. Environmental studies, including investigation of climate suitability for new winegrowing regions, are therefore necessary to support decision-making and develop tools for choices such as the best-suited grapevine cultivars.

Planting vineyards in new regions requires insight on regional and future climate conditions. Investigation on climate suitability for winegrowing at various latitudes generally makes use of temperature-based indices and climate analogy with existing wine producing regions. Among these indices, the Winkler and Huglin indices are well adapted for temperature zoning of winegrowing areas (Winkler *et al.* 1974, Huglin 1978, Huglin and Schneider 1998). The Huglin index is widely used in the multi criteria climate classification of winegrowing areas (Tonietto and Carbonneau, 2004). It remained the index that showed the best correlations with the potential sugar ripeness in grapes (Huglin and Schneider, 1998), until more recent models were developed to predict phenological stages of vines and sugar ripeness of grape berries with greater accuracy. Among these, the Grapevine Flowering and Veraison model – GFV (Parker *et al.*, 2011, 2013) and the Grapevine Sugar Ripeness model – GSR (Parker *et al.*, 2020a) are particularly accurate. The GFV model was used to assess spatial variability in vine phenology during a growing season over a wine region in New Zealand (Parker *et al.*, 2014) and the GFV and the GSR models were both recently used to predict trends in phenology and sugar ripeness in Champagne (Parker *et al.*, 2020b). The use of these two models offers interesting methodological perspectives to support harvest decisions in existing wine producing regions and to support grapevine cultivar choices in emerging wine producing regions.

Therefore, we choose to apply these two phenological models to test an innovative methodology to study climate suitability for emerging winegrowing regions. It was implemented over the Brittany region situated to the north-west of France (Fig. 1). From the regional perspective, major impacts of climate change on agriculture in this region have been observed (Mérot *et al.*, 2012, Dubreuil *et al.*, 2012). For exemple, Beauvais (2021) recently highlighted that the phenology and yields of cereals were significantly impacted by the increased temperatures and summer droughts in Brittany and Normandy. This encouraged the agricultural sector to project adaptation scenarios (Tilly, 2019; Ligneau *et al.*, 2020) and explore agricultural opportunities. Drought-tolerant plant varieties for instance, such as alfalfa or sorghum, are being introduced in this region (Beauvais *et al.*; 2021). Viticulture can be considered as an option, as it was preliminarily investigated by Bonnardot and Quénol (2020), especially since vines have already been cultivated in this region in the past (Saindrenan, 2011; Bachelier, 2020) and are currently replanted first under the impulse of associations of wine enthusiasts to safeguard local heritage and more importantly since 2016 with new regulations leading to the authorization of the planting of vines and the establishment of commercial vineyards (decree n°2015-1903; https://www.legifrance.gouv.fr/jorf/jo/2015/12/31/0303). Hence, climate change is not the initial trigger for vine development in Brittany but, considering that increasing temperatures in this cool oceanic climate region improves the potential quality of the produced wines, it is a factor enhancing vine development in the region (Bonnardot and Quénol, 2020).

This study establishes a methodology to assess the thermal potential of an emerging wine-growing region for the maturity of different grape varieties, using recently published indices in order to support decision-making regarding the choice of grape varieties. It also develops knowledge of the climatic potential of Brittany for viticulture at fine resolution, to provide information to local farmers who wish to diversify their productions and, secondly, to the wine industry stakeholders to assess the nomadic scenario of adaptation for viticulture.

Material and Methods

Study area

The Brittany region stretches approximately between 47°N and 49°N of latitude and 1°W and 5°W of longitude and corresponds to the peninsula that is in the northwest of France (Fig. 1). Brittany is under the influence of an oceanic climate, rather mild and humid, with relatively little seasonal contrast. Relief consists of rolling hills with the highest altitude culminating at 385 m in what remains of the Hercynian chain. The economy of the region is mainly based on agriculture, where an intensive mixed crop-livestock system prevails in the interior while vegetable production occupies the coastal agricultural areas. Areas with vineyards are sporadically distributed throughout the region with an approximate total area of 100 hectares (ARVB, 2021; https://vigneronsbretons.bzh/). The study region (Fig. 1) includes the four departments of the Brittany region (*Côtes d'Armor, Finistère, Ille et Vilaine,* and *Morbihan*), and the bordering *Loire-Atlantique* department to the south (whose territory was part of historical

Brittany Region), to provide a climatic comparison with the closest commercial wine growing region in the Loire Valley. This study area therefore corresponds to an extended administrative Brittany region, yet for easy-reading purposes we will refer to it hereafter as "Brittany".

This research is based on the analysis of daily temperature data (including maximum and mean temperatures) of different types (observed and modelled data) and of some observed mid-veraison and maturity information at harvest from existing vineyards.

Temperature data

Observed temperature data from seven weather stations of the *Météo-France* synoptic network, representative of the regional climate variability of the study region, were used over the 1950-2020 period (when available): *Brest-Guipavas*, *Dinard-Pleurtuit*, *Lorient-Lann-Bihoué*, *Nantes-Bouguenais*, *Quimper-Pluguffan*, *Rennes-Saint-Jacques* and *Rostrenen* (Fig. 1). For easy reading, these weather stations are named respectively hereafter: Brest, Dinard, Lorient, Nantes, Quimper, Rennes and Rostrenen.

Modelled climatic data at 8 km spatial resolution were downloaded from the Drias platform (http://www.drias-climat.fr/ 2014 dataset). The dataset for the study area corresponded to a total of 534 points (Fig. 1). The data generated by the French climate model developed by the National Center for Meteorological Research (CNRM) (Nabat *et al.* 2020, Daniel *et al.* 2019) and the European Center in Research and Advanced Training on Scientific Computing (CERFACS) were used to study climate future over the study region in the continuity of previous works (Bonnardot and Quénol 2020, Zavlyanova, 2020), namely the "CNRM-CM5/RCA4" which is a median model within the EURO-CORDEX CMIP5 GCM/RCM ensemble in terms of temperature (Drias 2020, http://www.drias-climat.fr/).

The daily temperature data were retrieved over two periods:

– the historical period (1976-2005) to assess the climate model performance against the observed data. Data for the seven meteorological stations enumerated before, were compared to data from the nearest grid point of the Drias database to identify the model biases.
– the future period running to 2100 to analyze the future climatic conditions.

The future period was subdivided into two periods of 30 years (according to the WMO standard climatic norm in climatology: a mid-term period (2031-2060) and a long-term period (2071-2100). These projections were analyzed for two GHG emission scenarios (RCP4.5 and RCP 8.5) (Moss *et al.*, 2010).

Grapevine phenology and berry maturity data

Although the number of plots with existing grapevines is limited in the study region, some grapevine phenology (date of mid-veraison) and berry maturity (sugar levels) data were collected from two grower associations (locations of the plots on Fig. 1). From plot 1, situated to the south of Ille-et-Vilaine half-way between the Rennes and Nantes weather stations, we obtained the dates of veraison observed on Pinot noir of a vine planted in 2009 for two seasons (2018 and 2019). From Plot 2, situated to the south of Finistère close to the weather station of Quimper, we obtained the dates of harvest and sug-

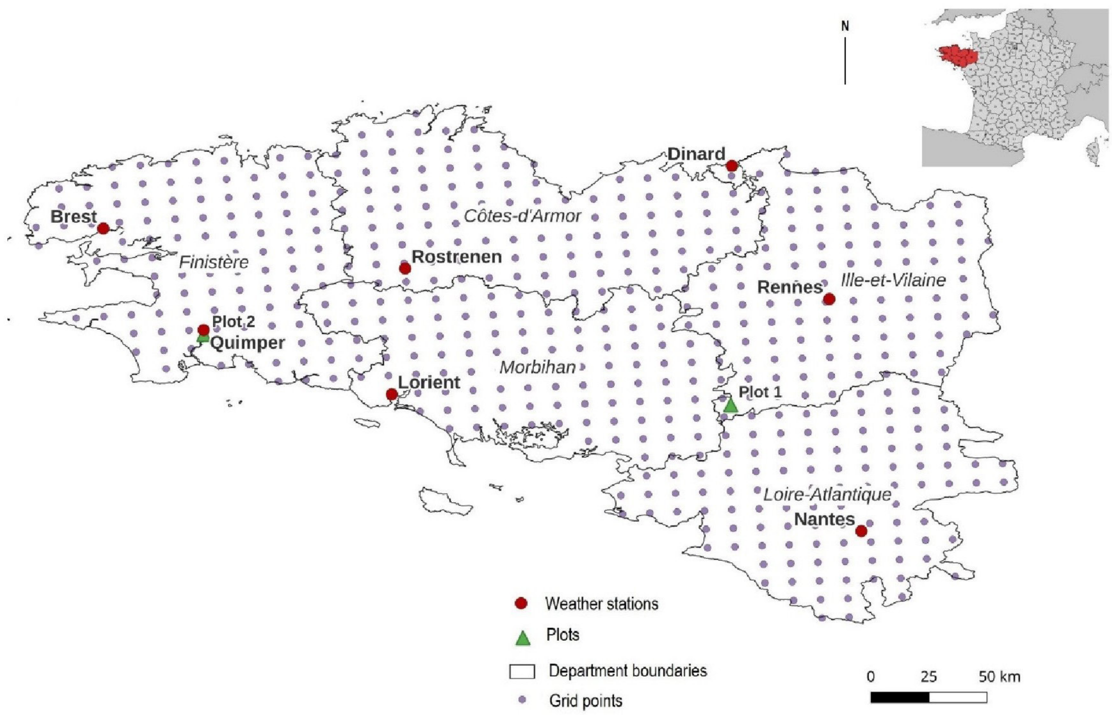

Fig. 1: Study area situated in the North-West of France and location of seven synoptic weather stations (red circles). Purple points (534) represent the gridded climatic dataset (Drias-climat.fr) and green triangles identify the grapevine plots on which agronomic data were collected.

ar level (expressed as the potential alcohol content) estimated by a densimeter from a vineyard of 'Chardonnay' planted in 2006 for two seasons (2009 and 2010).

The research methodology is based on the calculation and spatialization of bioclimatic indices for viticulture over historic and future periods: the Huglin heliothermic index (Huglin, 1978) and two more recent bioclimatic indices, the Grapevine Flowering and Veraison model (GFV; Parker *et al.*, 2011) and the Grapevine Sugar Ripeness model (GSR; Parker *et al.* 2020a).

Assessment of the climatic model to make methodological choices

The first step of the analysis is the assessment of the model used in this study over the historic period, *i.e.*, the comparison between modelled and observed climatic data for the seven weather stations. This enables the model bias to be analyzed, which is needed for the interpretation of the results related to the future period. This comparison was performed for the 1976-2005 period in a previous work (Zavlyanova, 2020). Major results regarding the growing season mean and maximum temperatures, which are used for the calculation of bioclimatic indices, are summarized in Table 1. Regarding mean temperatures, differences between modelled and observed data showed an overall slight but significant underestimation by the climatic model (except for Nantes), whose magnitude depended on location and season. The greatest difference was noted in spring for Lorient and Rostrenen and reached 0.4 °C. Regarding maximum temperatures, underestimation was in general greater than for mean temperatures in both seasons, varying from 0.8 °C in Nantes to 1.6 °C in Lorient.

These under-estimations and/or local over-estimation of the modelled temperatures impact the calculation of the bioclimatic indices and will be considered in the analysis of the results.

Calculation of the Huglin index

The Huglin index was originally established to estimate the thermal requirements for grape ripening and was better correlated with grape sugar levels (an overall 180-200 $g \cdot L^{-1}$ content) than the Branas and Winkler indices (Huglin and Schneider, 1998). This index was later combined with other climatic variables for the establishment of the multicriteria climate zoning of winegrowing regions (Tonietto and Carbonneau, 2004) and largely used since (e.g. in Santos *et al.*, 2012, Koufos *et al.*, 2018).

The Huglin index (HI) is based on a temperature summation, that considers daily mean and maximum temperatures above 10 °C as well as a coefficient of latitude (to take into consideration day length). The temperature accumulation is computed over the growing season of the vine, between the 1st of April and the 30th of September for the northern hemisphere (3) (Huglin, 1978).

$$HI = \sum_{1April}^{30September} \frac{(T_{md} - 10°C) + (T_{xd} - 10°C)}{2} \times k \quad (3)$$

T_{md} = Daily mean temperature in °C.

T_{xd} = Daily maximum temperature in °C.

k = coefficient of latitude ranging from 1.02 for latitude 40 to 1.06 to latitude 50. A coefficient of 1.05 was assigned to Lorient, Nantes, Quimper and Rennes and 1.06 to Brest, Dinard and Rostrenen.

This index was computed over the historic period (1976-2005) using the observed data and plotted at the seven weather stations to compare these locations and show the inter-annual variability and trend of the thermal conditions for viticulture since 1950 until present in this region. Furthermore, given that a statistically significant change in temperature since the 1980s on the observed time series was shown by means of the Pettitt *t* test (Zavlyanova, 2020), the historic period was subdivided into three periods for further interpretation of the results: before and after the significant change, *i.e.* 1950-1979, and 1980-2009 respectively and the most recent decade (2010-2020). The Huglin index was also calculated using the modelled datasets over the future period for two timelines (2031-2060 for the mid-term period and 2071-2100 for the long-term period) and two GHG emission scenarios (RCP4.5 and RCP8.5). The analyses were performed on the model grid points nearest to the weather stations.

The use of the Grapevine Flowering and Veraison (GFV) and Grapevine Sugar Ripeness (GSR) models for a selection of grapevine varieties

The Grapevine Flowering Veraison (GFV) model (Parker *et al.*, 2011, 2013) is a linear phenological model (temperature summation). It was established from a large database of phenology observations of grape varieties cultivated under different climatic conditions from many wine regions in the world across many years, to support the prediction of dates of mid-flowering (F) and mid-veraison (V) of the vine, corre-

Table 1: Spring and summer temperature differences (in °C) between modelled and observed data over the 1976-2005 period for specific locations in Brittany (extracted from Zavlyanova 2020)

Variable	Season	Dinard	Lorient	Nantes	Quimper	Rennes	Rostrenen
Mean Temperature	Spring	-0.2	-0.4	+0.1	-0.3	-0.2	-0.4
	Summer	-0.1	-0.3	+0.1	-0.3	-0.1	-0.3
Maximum Temperature	Spring	-1.4	-1.6	-0.8	-0.9	-0.9	-0.9
	summer	-1.4	-1.6	-0.8	-1.1	-1.0	-1.0

sponding respectively to stages BBCH 65 and 85 (Destrac-Irvine *et al.*, 2019). The average value (temperature summation) required to reach mid-flowering and mid-veraison is specific for each grapevine variety. This value corresponds to the cumulative daily mean temperature above 0 °C starting as from March 1st for the northern hemisphere (4) for which the dates for 50 % flowering or 50 % veraison are predicted, as indicated in Parker *et al.*, (2013).

$$GFV = \sum_{1March}^{(CfTable)} Tmd \quad (4)$$

T_{md} = daily mean temperature above 0 °C.

The Grapevine Sugar Ripeness (GSR) model, similar in conception to the GFV model, allows to determine target dates for specific sugar concentrations in grape berries, from 170 $g \cdot L^{-1}$ to 220 $g \cdot L^{-1}$. Thresholds were calibrated for a wide range of grapevine varieties. The cumulative daily mean temperature above 0 °C starting as from April 1st for the northern hemisphere (5) required for grape varieties to reach specific sugar concentrations in the berries have been published in Parker *et al.* (2020a).

$$GSR = \sum_{1April}^{(CfTable)} Tmd \quad (5)$$

Tmd = daily mean temperature above 0 °C.

The specific GFV and GSR thresholds were calculated for a selection of grapevine varieties. The study focuses on six grapevine varieties, chosen for their timing of ripeness, their potential to produce high-quality wine and successful utilization in commercial vineyards adjacent to the study area.

White grapevine varieties considered in this study:

- 'Sauvignon blanc' experiences very early ripening and has a high-quality potential for white wine production,
- 'Chardonnay' is a high-quality variety, widely cultivated and is only slightly later ripening than 'Sauvignon blanc'. It is also frequently grown at high latitudes (Clout, 2013, Nesbitt *et al.*, 2018) and can successfully be used to produce sparkling wines when harvested at low sugar levels (170 $g \cdot L^{-1}$),
- 'Chenin' is a later ripening variety and is a benchmark variety of the neighbouring Loire Valley.

Red grapevine varieties considered in this study:

- 'Pinot noir' is one of the earliest ripening varieties among the red cultivars and has a high-quality potential. It can also successfully be used for sparkling wine production when harvested at low sugar levels (170 $g \cdot L^{-1}$),
- 'Cabernet franc' is a high-quality variety and is a benchmark variety of the adjacent Loire Valley,
- 'Cabernet-Sauvignon' is a later ripening and high-quality variety, widely cultivated, also cultivated in Loire Valley, although being a minor variety there.

The GFV and GSR thresholds for these varieties were calculated using observed and modelled climatic data. They were computed using the observed temperature data to assess both grapevine models and to analyze the inter-annual variability and trend over the 1950-2020 period at the seven locations. They were used to determine the suitability of areas for viticulture over the study region, *i.e.*, the suitability to produce specific wine styles using certain targeted sugar level at specific dates.

Considering that the bias of the climate model on the mean temperatures over the 1976-2005 period was very small (Table 1), the GFV and GSR indices were computed using the climatic projections to analyze the future potential for viticulture in the region.

Validation of the output of the GFV and GSR models

Given grapevine cultivation is limited in this region, validation of the GFV and GSR grapevine models was performed using a limited set of mid-veraison and maturity data collected for 'Pinot noir' and 'Chardonnay' from growers.

For each field observation or measurement, two calculations were made:

- the GFV or GSR cumulative degree-day obtained for the day on which the specific observation or measurements in the plot was made, using the temperature data recorded at the nearest weather station. This value was compared to the GFV or GSR values required for the given cultivar to reach mid-veraison or targeted sugar levels according to Parker *et al.*, 2013, 2020a).
- the dates at which the required GFV or GSR values were reached for the year of the specific observation to compare with the dates of observation or measurement.

The two resulting differences (errors of prediction, as expressed in degree-day and numbers of days) contribute to assessing the performance of both grapevine models under the specific regional climate conditions. Unfortunately, not enough data was available for an extensive validation of the models in the study area.

Definition of the conditions for suitability and criteria for spatialization

In this study, the GFV model was used to predict mid-veraison and the GSR model to predict target sugar concentrations at harvest, namely 170 $g \cdot L^{-1}$ to produce sparkling wines, 190 $g \cdot L^{-1}$ for dry white wines and 200 $g \cdot L^{-1}$ for dry red wines. The GFV and GSR values that are required for the six selected cultivars to reach mid-veraison and different sugar ripeness targets are presented in Table 2.A.

The suitability for viticulture (*i.e.*, to produce different wine styles) was determined using specific deadlines to reach mid-veraison and sugar ripeness depending on the targeted wine style (Table 2B).

If the thermal requirement for mid-veraison was not reached by the 1st of September for dry wines or by the 15th of September for sparkling wines, it was considered too late for commercial wine productions (therefore unsuitable for the expected production), because the desired sugar ripeness level was unlikely to be reached. Likewise, the date of October 15th was considered as the deadline for grapes to reach the targeted sugar content. Beyond these dates, it was assumed that climatic conditions (decreasing temperatures and

Table 2. (A) Thermal requirements (in degree-days) for the selected grapevine varieties to reach mid-veraison according to the GFV model (Parker *et al.*, 2013) and to reach three targeted levels of sugar ripeness according to the GSR model (Parker *et al.*, 2020a). (B) Deadlines at which mid-veraison and selected target sugar levels should be reached to determine suitability for viticulture according to various objectives of production (sparkling and/or dry wines)

	Selected grape variety	Cumulative degree days required to reach the modelled date for mid-veraison	Cumulative degree days required to reach the modelled date to sugar concentration in grapes targeted at:		
			170 g·L^{-1}	190 g·L^{-1}	200 g·L^{-1}
(A) Thermal requirements (in degree-days)	Cabernet franc	2692	2683	2837	2909
	Cabernet-Sauvignon	2689	2797	2926	3031
	Chardonnay	2547	2723	2813	Not considered
	Chenin	2712	2798	2989	Not considered
	Pinot noir	2511	2695	2788	2838
	Sauvignon blanc	2528	2602	2719	Not considered
(B) Deadlines for mid-veraison and target sugar levels for various objectives of production	**Targeted wine style**	**Deadline to reach mid-veraison**	**Deadline to reach target sugar level**		**Target sugar level**
	Sparkling wine	15th of September	15th of October		170 g·L^{-1}
	Dry white wine	1st of September	15th of October		190 g·L^{-1}
	Dry red wine	1st of September	15th of October		200 g·L^{-1}

increasing rainfall) would no longer allow grapes to achieve the desired level of ripeness.

The GFV and GSR thresholds were also calculated for each selected red and white grapevine variety at the 534 points of the study region (Fig. 1) using the modelled datasets over the future period for two timelines (2031-2060 for the mid-term period and 2071-2100 for the long-term period) and two GHG emission scenarios (RCP4.5 and RCP8.5).

The deadlines to determine suitability according to the expected production of wine style (Table 2B), were used for two calculations: the average over the considered period and the percentage of years with fulfilled requirements. At first, GFV values for the 1st and the 15th of September, as well as the GSR value for the 15th of October, were averaged over the different periods and scenarios to obtain, at each point, for each deadline and each period and scenario, an average value beyond or below which viticulture was determined as unsuitable or suitable according to the expected production of wine style. These mean values were mapped to produce a general image of the suitable areas for viticulture in the region. The spatialization was performed using the QGIS software and the interpolation between points using the inverse distance weighting (IDW) method (Ly *et al.*, 2013). Secondly, the percentage of years within each period that met the different requirements to reach mid-veraison and targeted sugar levels at selected deadlines was calculated in order to consider the interannual variability. The percentage of suitable years for each study period was a means for assessing the economic viability of viticulture in the region.

The resulting maps and percentage graphs for each grapevine variety were used to analyze the overall potential of the emerging region to produce specific wine styles depending on future periods and GHG emission scenarios.

Results

Interannual variability and trend of the Huglin index (1950-2020)

The average values of the Huglin index remain very low (and very often below 1500 if we consider the inter-annual data) during the first 30-year period (1950-1979) and increase starting in the mid-1980s (Fig. 2). Based on the minimum thermal requirement provided by Huglin and Schneider (1998) for the earliest cultivars (1500-degree days for 'Müller-Thurgau' and 'Blauer Portugieser'), the thermal conditions experienced in the region during the 1950-1979 period were unsuitable for viticulture. This result points out the limit of the use of the Huglin index, as the *Loire-Atlantique* department (associated to the curve of Nantes on Fig. 2) is a well-known region producing dry white wine ('Muscadet'). The Huglin index is significantly higher over the period 1980-2009, showing improvement in thermal conditions for viticulture over the area. The value of the index was, on average during this period, over 1500 degree-days in Rennes and Nantes and close to 1500 in Lorient. For the other stations, the mean value has also been increasing since 1950 until today but still remains below 1500 degree-days in most years.

Hence, Huglin index shows increasingly suitable thermal conditions for viticulture over the past 70 years for viticulture in the Brittany region. Values are situated in the very cool or cool climate class according to the climatic classification of Tonietto and Carbonneau (2004).

Simulations show that the Huglin index will reach average values above 1500 units for all stations considered (except Rostrenen and Dinard) for the 2031-2060 period under the RCP4.5 and 8.5 scenarios (data not shown). For the 2071-2100 peri-

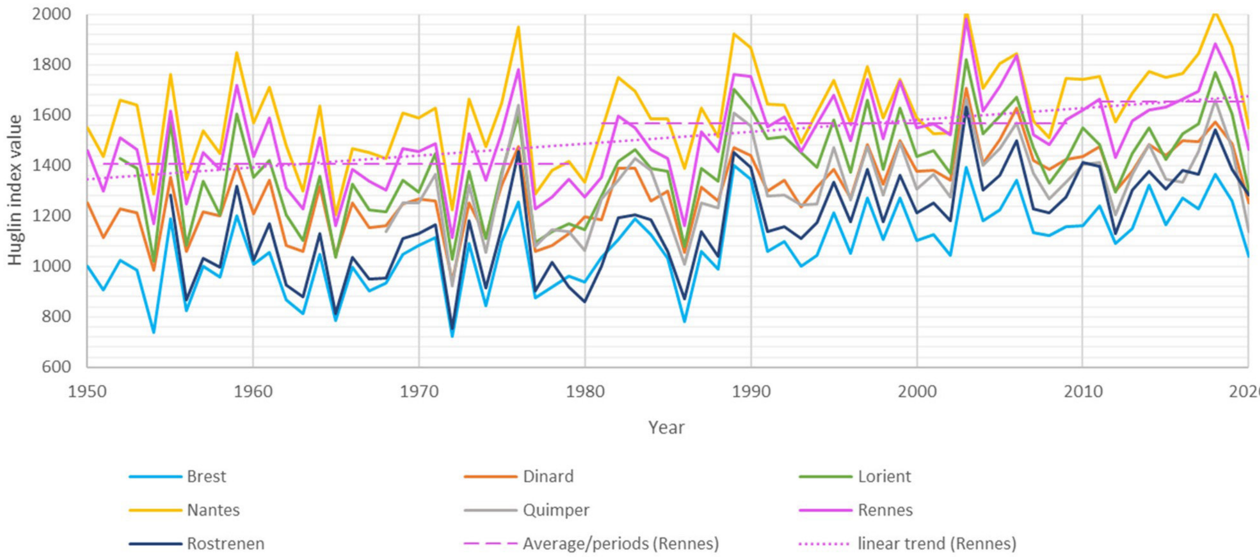

Fig. 2: Huglin index calculated using observed data from the seven weather stations located in the study area from 1950 through to 2020.

od, according to modelled climate data using the RCP4.5 scenario, all the measurement points will reach a mean Huglin index greater than 1500 and Rennes, Lorient and Nantes will be in the "temperate" class (>1800). According to modelled climate data using the RCP8.5 scenario, all points will reach values above 1900 and Rennes, Nantes and Lorient will have a Huglin index greater than 2100 ("warm temperate").

Due to the limits of the Huglin index to distinguish fine levels of sugar as defined for the study (Table 2B), GFV and GSR models were tested to provide deeper insight in the suitability for wine growing in Brittany. The GFV and GSR models were applied to the historical and future periods. These data were spatialized to study the suitability of a set of six grapevine varieties for quality viticulture in Brittany.

Partial validation of the GFV and GSR models with phenology observations and grape sugar data recorded in existing parcels in Brittany

Modelled and observed dates for veraison and sugar ripeness are presented in Table 3. Errors of prediction range from 2 to 16 days.

At Plot n°1, for 'Pinot noir' in 2018 and 2019, the degree-days that were obtained with the GFV model (computed with the temperature data of Nantes) for these dates resulted in a difference of 16 to 5 days, respectively, as compared with the GFV value required for 'Pinot noir' to reach mid-veraison according to Parker *et al.*, 2020a. At Plot n°2, for 'Chardonnay' in 2009 and 2010, the highest sugar concentration target for 'Chardonnay' as indicated in Parker *et al.*, (2020a) is 200 g·L^{-1}. The 200 g·L^{-1} sugar level was used as it was the closest sugar level to the one measured. Using the temperature data of Quimper, the GSR model predicted the dates of the 10th of October for 2009 and the 8th of October for 2010, for a sugar level of 200 g·L^{-1}. The differences between the modelled and observed dates for 'Chardonnay' in Quimper reach 7 days, in 2009.

Evolution of GFV and GSR thresholds over the 1950-2020 period and current conditions to produce dry white and red wines in Brittany

Annual dates of mid-veraison for 'Pinot noir' and targeted sugar levels for 'Pinot noir' and 'Chardonnay' were modelled using the temperature data of Brest, Dinard, Lorient, Nantes,

Table 3: Errors in prediction of the GFV and GSR grapevine models tested on four field observations in Brittany grown with 'Pinot noir' and 'Chardonnay' as expressed in number of days

Observed information	Date at which the required GFV or GSR values is reached for the year of the specific observation	Errors of prediction as expressed in days (Modelled date – observed date)
Date of Pinot noir Veraison at Plot 1 in 2018: 4 August	20 August	- 16 days
Date of Pinot noir Veraison at Plot 1 in 2019:18 August	13 August	5 days
Potential alcohol of 11.9% (200 g/L sugar) of Chardonnay harvested at Plot 2 on 17/10/2009	10 October	7 days
Potential alcohol of 12.2% (210 g/L sugar) of Chardonnay harvested at Plot 2 on 10/10/2010	8 October	2 days

Quimper, Rennes and Rostrenen. The output allowed analyzing the evolution of GFV and GSR indices over the 1950-2020 period and the potential to produce dry and red wines (Fig. 3, A-C).

The increasing regional temperatures induce earlier modelled dates of mid-veraison (Fig. 3A) and sugar ripeness (Fig. 3, B-C), although inter-annual variability remains high. Thermal requirements of mid-veraison and expected sugar levels are met in the last decade (2010-2020) for most of the stations in most of the year. Comparing the periods of 1950-1980 and 1981-2010, the sugar ripeness was advanced by

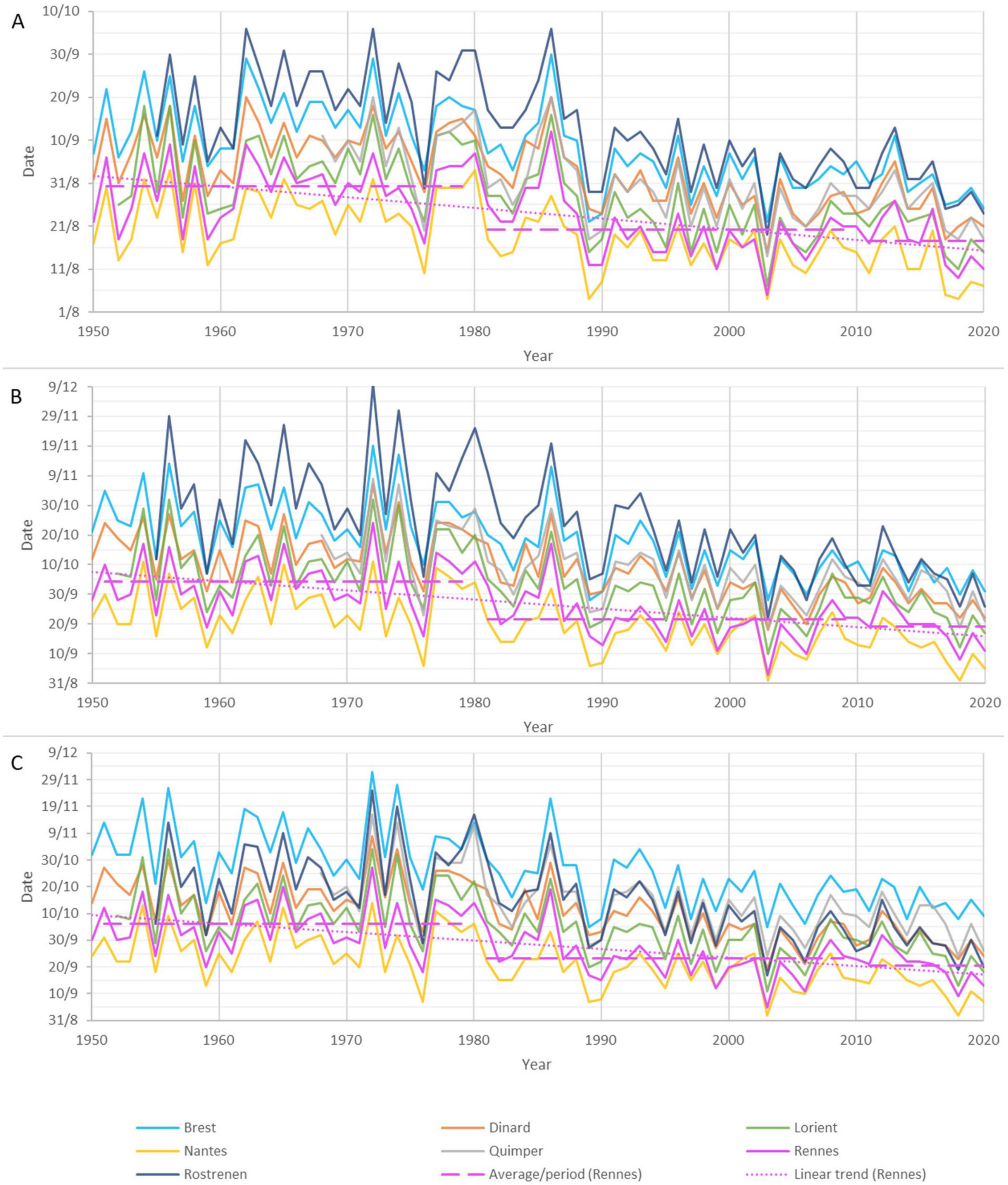

Fig. 3: (A) Modelled dates of mid-veraison for 'Pinot noir' by using the GFV index. (B) Modelled dates of sugar ripeness for a target sugar level of 190 g·L-1 (11.2 % potential alcohol) for 'Chardonnay' by using the GSR index, and (C) modelled dates of sugar ripeness for a target sugar level of 200 g·L-1 (11.7 % potential alcohol) for 'Pinot noir' by using the GSR index over the 1950-2020 period, at seven weather stations on Brittany with averages/periods and linear trends for Rennes weather station.

approximately one week. Hence, temperature conditions are becoming increasingly suitable for grape growing in Brittany.

Spatialization of mean dates for mid-veraison and sugar ripeness levels under different climate change scenarios for future periods 2031-2060 and 2071-2100

Maps displayed on Figs. 4-8 represent the areas for which mid-veraison and different target sugar levels of various cultivars are reached at selected deadlines (1/09 and 15/09 for mid-veraison and 15/10 for sugar ripeness) on average over two thirty-year periods (2031-2060 and 2071-2100) under different climate change scenarios (RCP 4.5 and RCP 8.5). Identification of suitable localities using the selected criteria presented in Table 1 are discussed in the following sections according to various objectives of wine production.

Identification of localities suitable to produce sparkling wines

To produce sparkling wines, suitable localities are those where 'Chardonnay' and 'Pinot noir' grapes are projected to reach mid-veraison before the 15th of September and a concentration of 170 g·L^{-1} of grape sugar is reached before the 15th of October as explained in Table 1.

Considering the 2031-2060 period, the mid-veraison of 'Pinot noir' and 'Chardonnay' is projected to occur before this date, on average, in most sectors of the region, yet it would remain a challenge in the extreme north-west and central parts of Brittany as shown in Fig. 4 under the conditions of RCP 4.5. The entire region would turn suitable considering the end of the century (results not shown as maps are fully colored).

Moreover, if mid-veraison is projected to be reached before the threshold date of the 15th of September, the targeted sugar ripeness of 170 g·L^{-1} should be reached before the 15th of October. This is the case over the entire region whatever scenario or horizon considered (data not shown). This means that even if mid-veraison seems to be challenging in the north-west of Brittany to make sparkling wine (Fig. 4), it is still possible that a suitable sugar ripeness can be obtained before the 15th of October.

Identification of localities suitable to produce dry white wines

Mid-veraison would be reached for the earliest white grapevine varieties ('Sauvignon blanc' and 'Chardonnay'), on average, before the 1st of September in nearly the entire region over the 2031-2060 period, whether under the RCP 4.5 (Fig. 5 top) or RCP 8.5 (Fig. 5 middle) conditions. During this mid-term period, these varieties would fail to reach mid-veraison before this date only in the north-western part of the region. Towards the end of the century (2071-2100), 'Sauvignon blanc' would reach this phenological stage before the 1st of September over the entire area under both scenario conditions (as shown for example for the RCP 4.5 in Fig. 5 bottom). 'Chardonnay' would reach it over a greater surface than for mid-century under the RCP4.5 conditions (Fig. 5 bottom) and over the entire area under RCP8.5 conditions (not shown). Regarding 'Chenin', which is the most cultivated grape variety in the neighboring Loire Valley, mid-veraison would be reached before the 1st of September during the mid-term period in the whole *Loire-Atlantique* department as well as in the south of *Ille-et-Vilaine* and *Morbihan* (Figs. 5 top and middle). During the long-term period, the areas where mid-veraison of 'Chenin' could be reached on time, extends gradually in north-west direction, covering the entire departments of both *Ille-et-Vilaine* and *Morbihan*, the east of *Côtes d'Armor* and the south of *Finistère* under the RCP 4.5 scenario (Fig. 5 bottom) and the entire region under the RCP 8.5 scenario (results not shown).

'Sauvignon blanc' and 'Chardonnay' would reach the sugar ripeness target of 190 g·L^{-1}, before the 15th of October, on average, over the entire study area, whatever scenario or timeline considered (results not shown). For 'Chenin', this target sugar level would not be reached, on average, in the north-west of Brittany during 2031-2060 whether RCP 4.5 or RCP 8.5 is considered (Fig. 6). Nevertheless, during the long-term period, even 'Chenin' would ripen up to a sugar concentration level of 190 g·L^{-1} over the entire study region (results not shown).

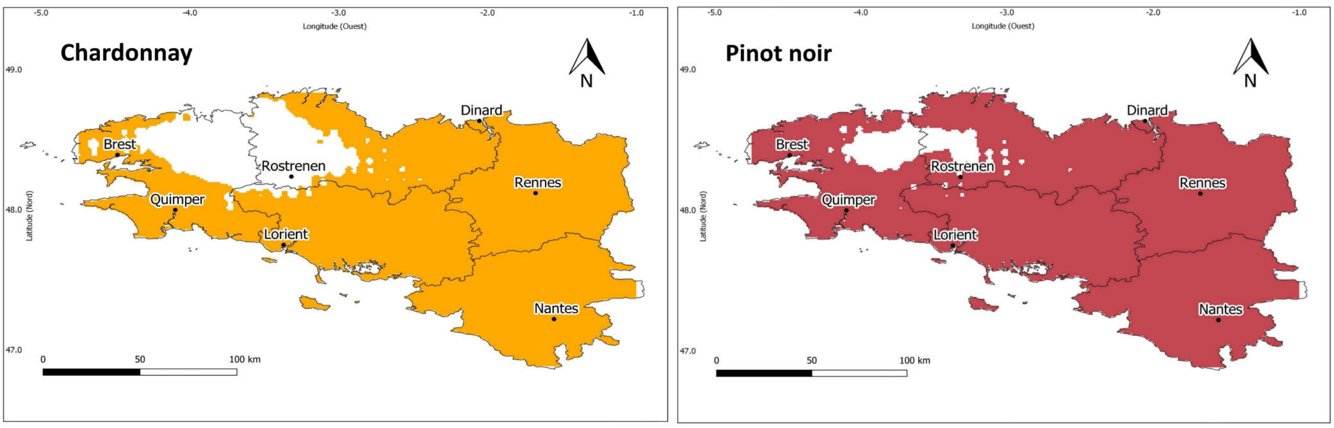

Fig. 4: Regions in *Brittany* (colored areas) where mid-veraison of 'Chardonnay' (left) and 'Pinot noir' (right) is reached before the 15th of September according to the GFV index, for the 2031-2060 period under RCP 4.5.

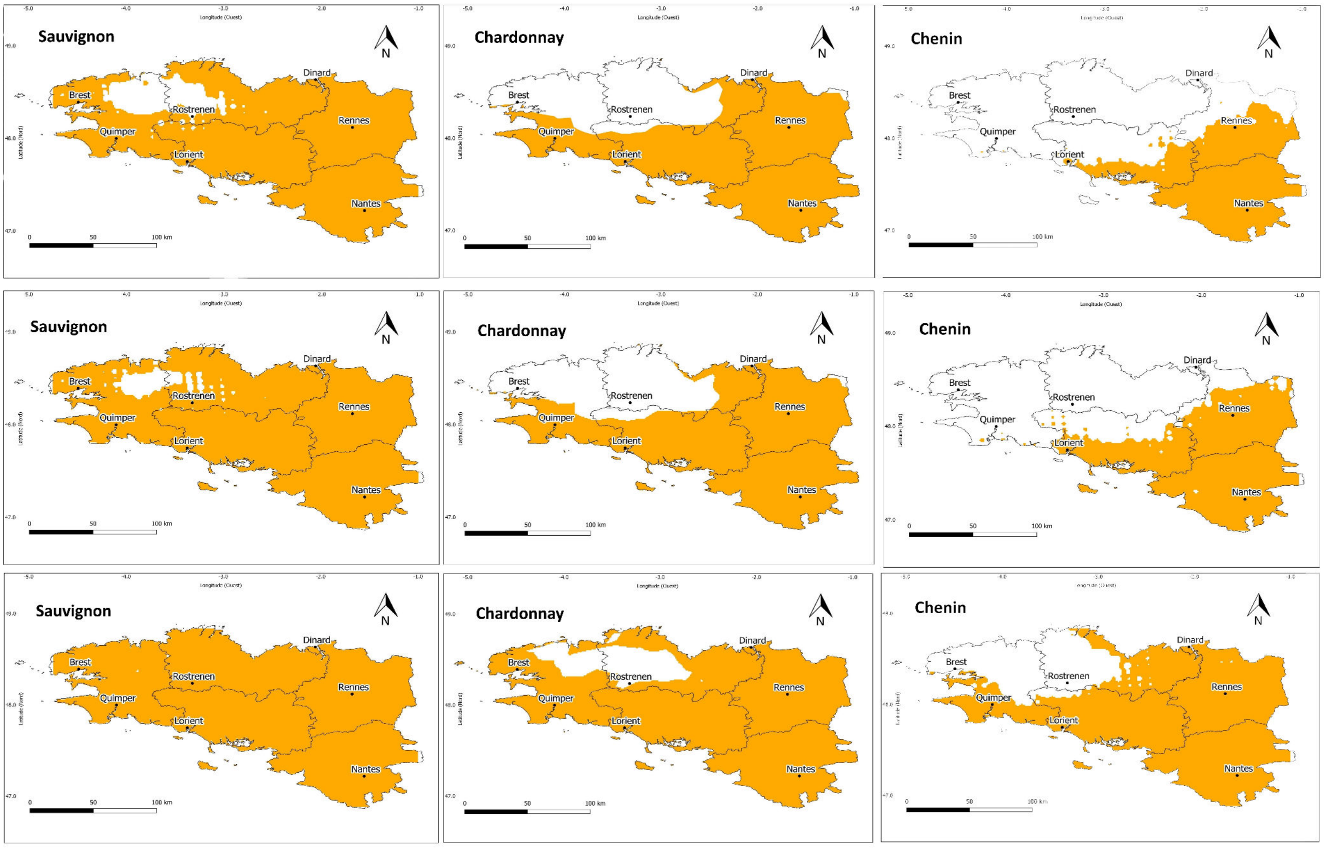

Fig. 5: Regions in *Brittany* (colored areas) where mid-veraison of 'Sauvignon', 'Chardonnay' and 'Chenin' is reached before the 1st of September according to the GFV index, for the 2031-2060 period under the RCP 4.5 (top) and RCP 8.5 (middle) conditions and for the 2071-2100 period under RCP4.5 conditions (bottom).

Identification of localities suitable to produce dry red wines

In the time frame 2031-2060, mid-veraison would be reached for red grapevine varieties 'Pinot noir', 'Cabernet-Sauvignon' and 'Cabernet franc', on average, before the 1st of September over half of the region only (the south and east) or more for the early cultivar 'Pinot noir' under RCP 4.5 (Fig. 7 top). The surface meeting these requirements extends progressively towards the northwest under the RCP 8.5 (Fig. 7 middle) or during the end of the century (Fig. 7 bottom). 'Pinot noir' would reach this phenological stage during the long-term period of 2071-2100 before the 1st of September over the whole area under RCP 8.5 as soon as 2031-2060 (Fig. 7 middle), while 'Cabernet-Sauvignon' and 'Cabernet franc' would reach it over the entire region by the end of the century under RCP 8.5 only (results not shown).

The mapping of areas where thermal conditions would allow red grapevine varieties to reach sugar ripeness at 200 g·L^{-1} is in accordance with those of mid-veraison. The early ripening 'Pinot noir' cultivar would reach this target sugar level before the 15th of October over the whole region as soon as 2031-2060 whatever the scenario; while the late maturity cultivars

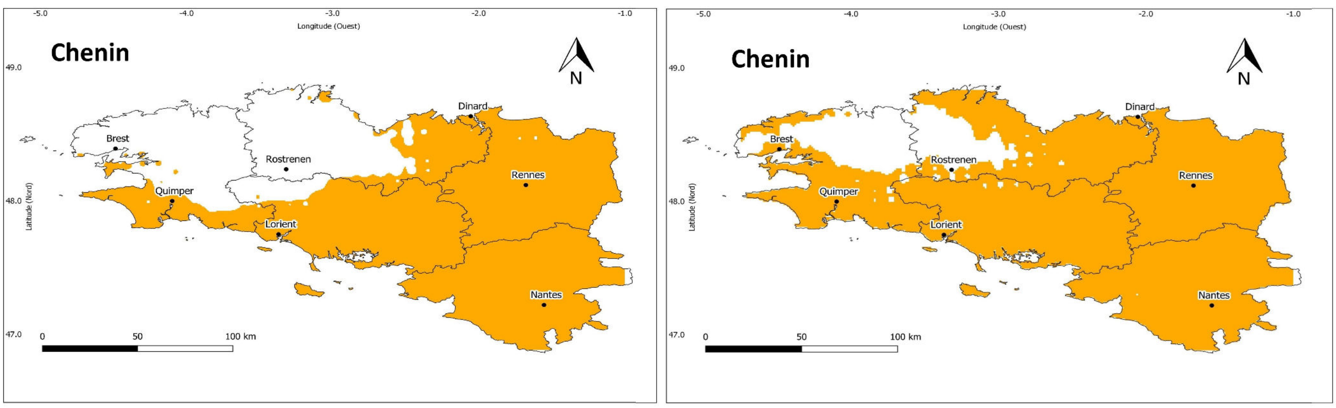

Fig. 6: Regions in *Brittany* (colored areas) where the mean target sugar level of 190 g·L-1 is reached before the 15th of October on average for the 2031-2060 period under RCP 4.5 (left) and RCP 8.5 (right) conditions.

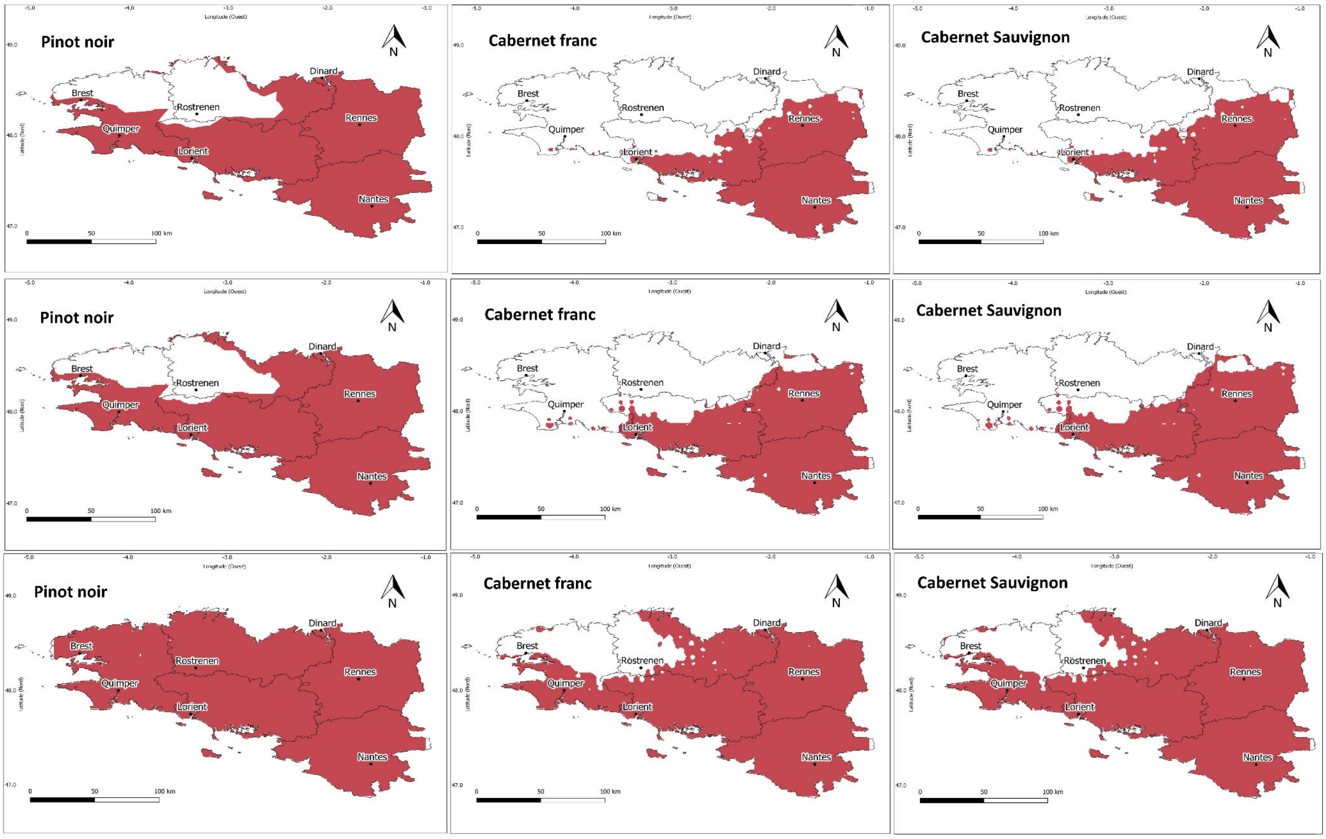

Fig. 7: Regions in *Brittany* (colored areas) where mid-veraison of 'Pinot noir', 'Cabernet franc' and 'Cabernet Sauvignon' is reached before the 1st of September according to the GFV index, for the 2031-2060 period under RCP 4.5 (top) and RCP 8.5 (middle) conditions and for the 2071-2100 period under RCP4.5 conditions (bottom).

'Cabernet franc' and especially 'Cabernet Sauvignon' would not reach it before this date in the north-west of Brittany during 2031-2060 under RCP 4.5 but RCP 8.5 (Fig. 8). Nevertheless, these two red grapevine varieties would reach 200 g·L^{-1} of sugar concentration before the 15th of October, on average, across the whole region during the long-term period (results not shown).

Identification of commercial viticulture viability

Figs. 4 to 8 identify localities where mid-veraison and target sugar ripeness levels would be reached on average before critical dates over two thirty-year periods, but do not consider inter-annual variability. Therefore, the percentage of years meeting various targets and deadlines set up in this study is displayed to assess viability of commercial viticulture de-

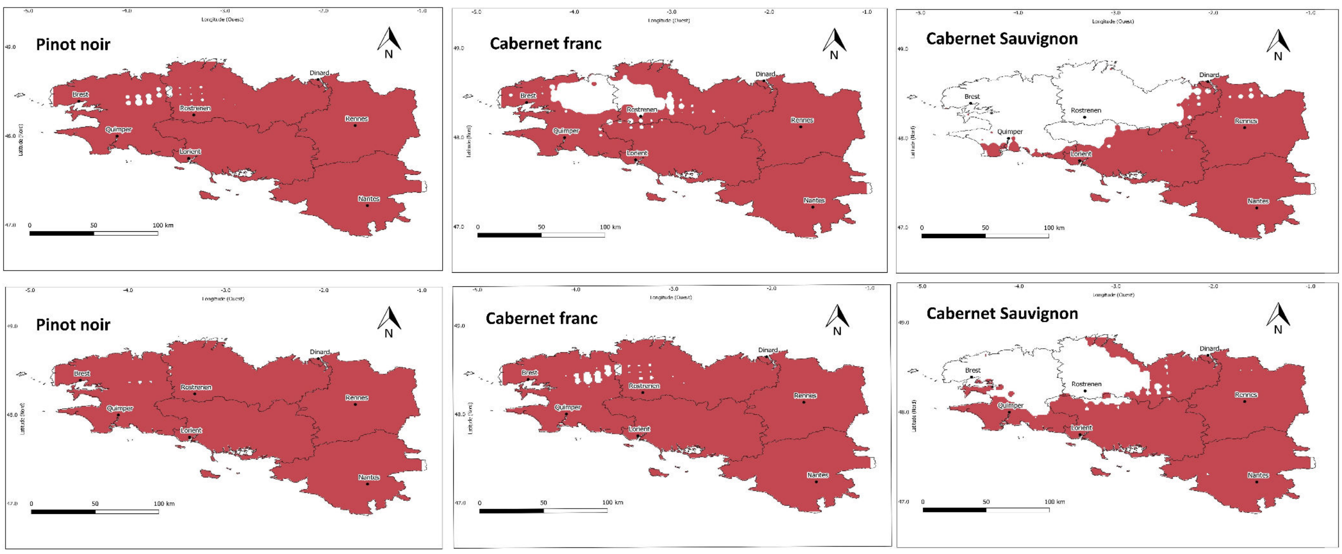

Fig. 8: Regions in *Brittany* (colored areas) where 'Pinot noir', 'Cabernet franc' and 'Cabernet Sauvignon' reach the mean target sugar level of 200 g·L-1 before the 15th of October on average for the 2031-2060 period under the RCP 4.5 (top) and RCP8.5 (bottom) conditions.

pending on the objective of producing still wines: percentage of years with mid-veraison reached before the first of September (Figs. 9, A and B) and with sugar targeted at 190 g·L^{-1} for white wines and 200 g·L^{-1} for red wines reached before the 15th of October (Figs. 9, C and D). The example is given for one station, Rostrenen, where viticulture is the most challenging, in order to highlight the methodology.

Considering the 1st of September as the deadline for mid-veraison to be reached (Figs. 9 A and B), the percentage of suitable years is greater for cultivation of early cultivars ('Sauvignon blanc', 'Chardonnay' and 'Pinot noir') than for late cultivars ('Cabernet franc', 'Cabernet-Sauvignon' and 'Chenin') and reached at least 80 %, especially at the end of the century under the RCP 8.5 conditions as shown for Rostrenen station as an example. At the northernmost and/or westernmost stations, the cultivation of the late cultivars for dry wines remains economically challenging during the short-term period under the RCP 4.5 scenario but the viability is considerably improved during the long-term period and the RCP 8.5 conditions (Fig. 9 B and D). For the production of sparkling wines, however, the percentage of suitable years reached 100 % at all stations leading to a viable commercial activity (as shown for Rostrenen in Fig. 9 D).

Discussion

This study assessed the thermal potential of Brittany using the GFV and GSR grapevine models to assist in the decision-making process for grape variety selection. The scientific approach of using these phenological models with temperature data from weather stations and modelled data from future climate projections allowed spatial and temporal estimation of the suitability of grape varieties for viticulture in Brittany.

Contribution and limits of the Huglin index to assess viticultural suitability

Computing the Huglin index over the historical period allowed assessment of the thermal conditions and comparison with existing wine producing regions. The Huglin index increased over the historical period, with an acceleration since 2010, confirming the regional impact of climate change in Brittany. The index was, however, often under 1500 units at most stations, a threshold that Huglin considers as the minimum thermal requirement for the earliest cultivars to reach a sugar content of 180-200 g·L^{-1}. The target sugar level is too coarse and so are the threshold values provided for a range of varieties in Huglin and Schneider (1998). In comparison, the more recent GFV (for flowering and mid-veraison) and GSR (for sugar ripeness) models provide a more precise framework to assess the suitability of a given region for wine production (Parker *et al.* 2011, 2013, 2020a). Hence, in this work, the Huglin index was used to analyze temperature trends over historical and future periods only, while spatial projections for the suitability for viticulture in Brittany were based on the GFV and GSR models.

Assessment of the performances of the GFV and GSR models

Because viticulture is currently marginal in Brittany, only a limited number of field observations for mid-veraison and grape sugar levels were available to attempt assessing the accuracy of the GFV and GSR models under the climatic conditions of Brittany. Moreover, some of the vineyards in production are still very young and there is no scientific monitoring protocol that can ensure the quality of the collected data. Keeping in mind these limits, comparison of observed and modelled dates resulted in a difference on average of 10 days for mid-veraison and 4 days for targeted sugar ripeness dates (Table 2). The magnitude of the error is slightly greater or comparable to those published in Parker *et al.* 2020b, where errors in prediction of mid-veraison were less than 7 days for 87 % of the cultivars and years considered and errors in prediction of a target sugar ripeness level of 190 g·L^{-1} was less than 10 days for 94 % of cultivars and years. The main cause of discrepancy may come from the climate dataset that was used as not fully representative of the climate conditions that the grapevines experience locally. As more vineyards come into production in the coming years in Brittany, a systematic grapevine monitoring would offer access to greater spatial and temporal data for validation of the GFV and GSR models under these regional oceanic climate conditions. Furthermore, a weather station network within the vineyards of Brittany is under development to study the various cultivar responses to climate variability and will provide more accu-

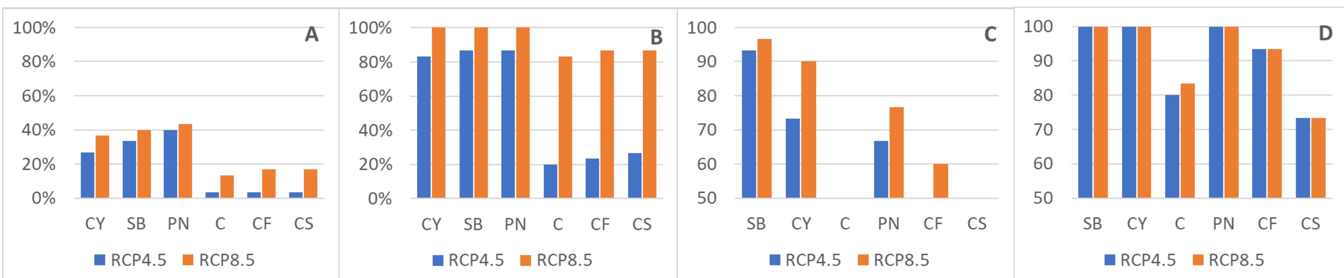

Fig. 9: Percentage of years at Rostrenen station with grape varieties reaching mid-veraison before the 1st of September under RCP 4.5 (in blue) and RCP 8.5 (in orange) climate change scenario for two-time frames: 2031-2060 (A) and 2061-2100 (B). Similar projections for grape varieties reaching sugar ripeness (190 g·L^{-1} for white cultivars and 200 g·L^{-1} for red cultivars) before the 15th of October for 2031-2060 (C) and 2061-2100 (D). CY stands for 'Chardonnay', SB for 'Sauvignon blanc', PN for 'Pinot noir', C for 'Chenin', CF for 'Cabernet franc' and CS for 'Cabernet-Sauvignon').

rate temperature measurements than those used in this paper (Bonnardot *et al.* 2022).

The spatialization of the GFV and GSR indices using the climatic projections of the CNRM-CM5/RCA4 climatic model across Brittany for two timelines (2031-2060 and 2071-2100) and two GHG emission scenarios (RCP 4.5 and RCP 8.5) showed a general viability for the commercial production of wines for three white and three red grapevine varieties selected for this study. However, for the mid-term timeline (2031-2060) under the climatic conditions of the RCP 4.5 scenario, it may remain challenging to reach mid-veraison in the north-west of Brittany before the 1st of September. Under the RCP 8.5 scenario and whatever the timelines considered; sugar ripeness is expected to be achieved before the 15th of October for most of the studied grapevine varieties. Ripening of 'Chenin' and 'Cabernet-Sauvignon' remains challenging during the 2031-2060 period for both GHG scenarios in the far north-west of the region. Moreover, while the Drias 2020 dataset is already used to study climate and viticulture in Brittany (Petitjean *et al.* 2022), a multi-model study should be further performed to consider the uncertainties linked to the different GCM/RCM combinations (Drias 2020). In this study, an 8-km spatial resolution dataset was used, which is common for studying climate change impacts at regional scales. Nevertheless, a finer resolution is required to study the impacts of climate change at local scales, for example at the scale of a parcel or a farm (Jones *et al.*, 2004; Quénol, 2014). Some other factors influence viticulture suitability, including topography, slopes and aspects, the presence of hedgerows or trees, soil properties (texture, coarse elements, drainage, soil depth to bedrock, water-holding capacity), and these were not considered in this research. Moreover, the actual plot surfaces under vineyards in Brittany cover 1 to 2 ha per parcel on average (5 ha for the largest ones), so a spatial resolution of 8 km is not refined enough to identify the best suited locations for viticulture. Although these other factors are obviously of importance, it was beyond the scope of this article to take them into account. This study aimed at assessing viticulture suitability on the regional scale of Brittany, or for the choice of grapevine varieties in general over the whole region.

Modelling framework used in this study

It should be noted that the uncertainties can be propagated throughout the modeling framework. The observed climatic data used over the historical period are retrieved from weather stations which are not located in vineyards and therefore may not be representative of thermal conditions at the plot scale. Climate projections that were used to study the future climatic conditions represent possible futures according the GHG emission scenario. Moreover, temperature projections were coupled to the phenology models GFV and GSR, for which the errors of predictions are specified in Parker *et al.* (2020b).

The regional climate projections used are those originally produced within the framework of the Euro-CORDEX at a 0.11° resolution (Giorgi, 2006), which were further projected on a grid of 8-km spatial resolution over France and corrected for their bias by the CDF-t method (Michelangeli *et al.*, 2009) from the analysis of SAFRAN observation data (Drias portal). These regional datasets are freely accessible and largely used by the scientific community in regional future climate assessments. The 2014 regional Drias dataset was used in this study as previously in Bonnardot and Quénol (2020) and Zavlyanova (2020).

A possible extension of this work would be to spatialize GFV and GSR indices based on temperature data produced by other climatic models to consider the uncertainties linked to climate models as the EuroCordex experience has shown differences across models, some warming more and other warming less (Drias 2020), the one that was used here being a median model in terms of warming intensity. The study could further be refined using the up-to-date regional climate projections dataset "Drias 2020" (Soubeyroux *et al.*, 2020), which was not available at the time of this analysis or using the SSP scenarios (Shared Socio-economic Pathways, IPCC, 2021) especially since an updated assessment of past and future warming over France based on a regional observational constraint (Ribes *et al.*, 2022) showed that climate projections over France are underestimated.

The use of temperature-based models to project the date of mid-veraison and sugar ripeness

The Winkler index was the first agro-climatic index which was widely used to characterize thermal conditions for winegrowing regions (Winkler *et al.*, 1974). Thereafter, the Huglin index (Huglin, 1978; Huglin and Schneider 1998) was proposed with degree-days calculated in a different way, putting more weight on maximum temperatures. It can be used for similar purposes, as is specified in Tonietto and Carbonneau (2004), but also to assess varietal suitability. Huglin published threshold values for this index for 26 varieties to reach sugar concentrations of 180-200 g·L^{-1}. However, the number of varieties published by Huglin is limited, a few major varieties are missing (such as 'Tempranillo', 'Sangiovese'), while some very minor varieties are present in the list ('Melon', 'Riesling Italien', 'Aramon', 'Blaufränkisch'). Moreover, Huglin's list contains some obvious inconsistencies: temperature threshold is lower for 'Cabernet franc' compared to 'Merlot' and 'Sémillon', while 'Cabernet franc' is without contest the later ripening variety of the three.

More recent GFV and GSR models can be used for a wider range of grapevine cultivars (Parker *et al.* 2013 and 2020a), and they were proven efficient and accurate at the variety level (Parker *et al.* 2020b). Target sugar levels range from 170 to 220 g·L^{-1} (Parker *et al.*, 2020a), so that the GSR model can be applied to assess the suitability of winegrowing areas for sparkling wine (target sugar level 170 g·L^{-1}) to dry white wine (190-200 g·L^{-1}) or dry red wine (200-220 g·L^{-1}). GFV and GSR are based on temperature summations with a base temperature of 0 °C and are easy to implement. In this work, we have chosen to combine the GFV model for veraison assessment with the GSR model for sugar ripeness assessment. In the northern hemisphere, the ripening window for grapevine closes around the 15th of October (van Leeuwen and Seguin, 2006). Grape ripening, starting at veraison, requires approximately 45 days to be achieved for the production of dry wines. Hence, the 1st of September was used as a threshold for mid-veraison to produce dry wines. This threshold was set at the 15th of September to produce sparkling wines, for which grapes are harvested with low sugar and high acidity. Sugar target levels were set at 170 g·L^{-1} for sparkling wine production, 190 g·L^{-1} for dry white wine production and 200 g·L^{-1} for red wine production, according to Parker *et al.* (2020a and b). If the methodology developed in this study is to be applied in other emerging winegrowing regions, target sugar levels can be easily adapted to the requirements of expected wines style. It should be noted that to produce red wine, grapes are often harvested at sugar levels higher than 200 g·L^{-1}, for wines meant to be aged several years before consumption. A target sugar concentration level was set in this study at 200 g·L^{-1}, which is adapted to produce fruity red wines for early consumption. It should also be noted that these target concentrations are not absolute values, e.g. sugar or must concentrate can be added to increase the alcohol content of the produced wine, blending can be performed with better years, or lower yields can be targeted to increase grape sugar content.

Climate suitability versus economic suitability

The maps of climate suitability that were produced can be considered as "optimistic" because an area was considered suitable when the threshold dates were met *on average* over the two thirty-year periods However, the average could have been skewed by a few high or low values. Inter-annual variability was not considered in these maps. Obviously, commercial viticulture is not viable when the percentage of unsuitable years is high.

Mapping the percentages of suitable years will be the object of further investigations, to give insight in the impact of inter-annual variability on commercial viability of viticulture. However, the occurrence of suitable years was already calculated for seven locations with the aim to produce dry white and red wines. This type of output is interesting for investors, who can decide what percentage of suitable years (e.g. 80 or 90 %) is required to make the plantation of vineyards financially viable.

Conclusion

The methodology developed in this research, which is based on the GFV and GSR models, can be applied to any emerging winegrowing regions in the world. The advantage of GFV and GSR models is that only daily mean temperatures are required to calculate projected dates to reach specific phenological stages or target sugar levels. With the large range of grapevine varieties calibrated for the GFV and GSR models, it is possible to extend this study to project the winegrowing potential for new regions with specific varietal choices. It may also be applied in existing winegrowing regions to adapt grapevine varieties to a changing climate. This methodology is very flexible with the ability to adjust thresholds as desired to specific needs of a specific region or wine style intended to be produced. Threshold dates that have been used in this study can be easily adapted to the type of wine targeted in a specific region, and it is possible to set more severe requirements for the assessment of suitability. Moreover, the use of percentages of suitable years can be helpful to project the economical sustainability of winegrowing in a specific region.

Acknowledgements

Research was undertaken within the framework of two projects: ACCAF-LACCAVE led by INRAE (UMR EFGV) and IRP-VINADAPT led by CNRS (UMR LETG 6565 CNRS). The authors wish to thank the wine growers who kindly provided us harvest and mid-veraison data. Our thanks also go to the reviewers who helped to improve this manuscript.

Conflicts of interest statement

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

References

Aigrain, P.; Bois, B.; Brugière, F.; Duchêne, E.; de Cortazar-Atauri, I. G.; Gautier, J.; Giraud-Heraud, E.; Hammond, R.; Hannin, H.; Ollat, N.; Touzard, J.M.; 2019: L'utilisation par la viticulture française d'un exercice de prospective pour l'élaboration d'une stratégie d'adaptation au changement climatique. In *BIO Web of Conferences* 12, 03020. EDP Sciences. DOI: 10.1051/bioconf/20191203020

Anonymous, 1938: Décret du 4 avril 1938 portant application de la loi du 13 janvier 1938 concernant le régime des appellations d'origine viticoles. (Modification de l'art. 7 du décret du 30 septembre 1936), p. 4189

ARVB Vignerons Bretons – Le site de l'Association pour la Reconnaissance des Vins Bretons. Available at: https://vigneronsbretons.bzh/ (Accessed: 28 September 2021)

Bachelier, J.; 2020: Vins et vignobles en Bretagne au Moyen Âge: Premières observations et perspectives, In: Vins, vignobles et viticultures atlantiques Quelles trajectoires contemporaines? *Norois* 2020/1 no. 254. Presses Universitaires de Rennes, France.

Beauvais, F.; 2021: Approches géographiques et agro-climatologiques des conséquences du changement climatique sur l'agrosystème céréalier de Normandie : constat et étude d'impact prospective appliqués au blé tendre d'hiver. Thèse de doctorat, Université de Caen Normandie, 532 p.

Beauvais, F.; Cantat, O.; Madeline, P.; 2021: Le maïs ensilage dans le Grand-Ouest français face au changement climatique à l'horizon 2100. Climatologie (18) https://doi.org/10.1051/climat/202118002

Bentzen, J.; Smith, V.; 2009: Wine production in Denmark. Do the characteristics of the vineyards affect the chances for awards. *Working paper 09-21*, Department of Economics, Aahrus University, Denmark.

Bonnardot, V.; Thibault, J.; Petitjean, T.; Tissot, C.; Quénol, H.; 2022: La vigne en Bretagne sous observation climatique. In: *Proceeding of 35th international congress of the Associa-*

tion Internationale de Climatologie, Météo-France Toulouse 2022 http://www.meteo.fr/cic/meetings/2022/aic/

Bonnardot, V.; Quénol, H.; 2020: Viticulture en Bretagne: challenge ou opportunité? Quelques indices bioclimatiques régionaux', in Bonnardot V., H. Quénol (Eds). Changement Climatique et Territoires. *AIC Proceedings*, 127-132. LETG UMR 6554 CNRS, Rennes, France.

Cabré, F.; Nuñez, M.; 2020: Impacts of climate change on viticulture in Argentina. *Regional Environmental Change,* **20,** 12. DOI: https: 10.1007/s10113-020-01607-8

Cardell, M.F.; Amengual, A.; Romero, R.; 2019: Future effects of climate change on the suitability of wine grape production across Europe. *Regional Environmental Change*, 19 (8), 2299-2310.

Cepnioglu, Y.: 2021: A suitability model with fuzzy logic: Wine industry suitability under changing climate. *Master thesis in Geography*, Umeå University, 28 p. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1564296&dswid=6874 (accessed on 21 July 2021).

Clout, H.; 2013: An overview of the fluctuating fortunes of viticulture in England and Wales, *EchoGéo*, (23). DOI: 10.4000/echogeo.13333.

Daniel, M.; Lemonsu, A.; Déqué, M.; Somot, S.; Alias, A.; Masson, V.; 2019: Benefits of explicit urban parameterization in regional climate modeling to study climate and city interactions. *Climate Dynamics*, 52 (5-6), 2745-2764.

Destrac-Irvine, A.; Barbeau, G.; de Rességuier, L.; Dufourcq, T.; Garcia de Cortázar-Atauri, I.; Ojeda, H.; Saurin, N.; van Leeuwen, C.; Duchêne, E.; 2019: Measuring phenology to more effectively manage the vineyard. *IVES Technical Reviews*, 1 October 2019.

Dubreuil, V.; Planchon, O.; Lamy, C.; Bonnardot, V.; Quénol, H.; 2012: Le changement climatique dans la France de l'Ouest: observations et tendances. In: P. Mérot et al. (Eds). Le climat change dans le Grand Ouest, Tendances, Impacts, Perceptions, 19-30. Presses Universitaires de Rennes, France.

Duchêne, E.; Huard F.; Dumas, V.; Schneider, C.; Merdinoglu, D.; 2010: The challenge of adapting grapevine varieties to climate change, *Climate Research*, 41, 193-204. DOI: 10.3354/cr00850.

Dunn, M.; Rounsevell, M.D.A.; Boberg, F.; Clarke, E.; Christensen, J.; Madsen, M.; 2019: The future potential for wine production in Scotland under high-end climate change, *Regional Environmental Change*, 19 (3), 723-732. DOI: 10.1007/s10113-017-1240-3.

Fraga, H.; Malheiro, A.-C.; Moutinho-Pereira, J.; Santos, J.A.; 2013: Future scenarios for viticultural zoning in Europe: ensemble projections and uncertainties, *International Journal of Biometeorology*, 57, 909-925. DOI: 10.1007/s00484-012-0617-8.

Fraga, H.; Garcia 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), 3774-3788. DOI: https://doi.org/10.1111/gcb.13382.

Garcia de Cortázar Atauri, I.; Caubel, J.; Quénol, H.; Bois, B.; Chuine, I.; Duchêne, E.; Leroux, R.; Parker, A.K.; van Leeuwen, C.; Ollat, N.; 2016: Assessment of future climatic conditions in French vineyards. Consequences for defining adaptation strategies. In: *ClimWine 2016* (Sustainable grape and wine production in the context of climate change).

Garcia de Cortázar Atauri, I.; Duchêne, E.; Destrac, A.; Barbeau, G.; De Rességuier, L.; Lacombe, T.; Parker, A.; Saurin, N.; van Leeuwen, C.; 2017: Grapevine phenology in France: from past observations to future evolutions in the context of climate change. *OENO One*, 51 (2), 115-126. DOI: 10.20870/oeno-one.2017.51.2.1622

Giorgi, F.; 2006: Climate change hot-spots. *Geophysical research letters*, 33 (8).

Hannah, L.; Roehrdanz, P. R.; Ikegami, M.; Shepard, A.V.; Shaw, M.R.; Tabor, G.; Zhi, L.; Marquet, P.A.; Hijman, R.J.; 2013: Climate change, wine, and conservation, *Proceedings of the National Academy of Sciences*, 110 (17), 6907-6912. DOI: https://doi.org/10.1073/pnas.1210127110.

Huglin, P.; 1978: Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. *Comptes Rendus de l'Académie d'Agriculture de France,* 64, 1117-1126.

Huglin, P.; Schneider, C.; 1998: *Biologie et écologie de la vigne*. Tec&doc-Lavoisier. Paris (France).

IPCC; 2021: Climate Change 2021: The Physical Science Basis. In: Masson-Delmotte, V., 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 (Eds). *Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jones, G.; White, M.A.; Cooper, O.R.; Storchmann, K.; 2005: Climate change and global wine quality. *Climate Change*, 73, 319-343. DOI: 10.1007/s10584-005-4704-2.

Jones, G. V.; Snead, N.; Nelson, P.; 2004: Geology and wine 8. Modeling viticultural landscapes: A GIS analysis of the terroir potential in the Umpqua Valley of Oregon, *Geoscience Canada*. Available at: https://journals.lib.unb.ca/index.php/GC/article/view/2779 (Accessed: 3 April 2021).

Koufos, G. C.; Mavromatis, T.; Koundouras, S.; Jones, G.V.; 2018: Response of viticulture-related climatic indices and zoning to historical and future climate conditions in Greece. *International Journal of Climatology*, 38 (4), 2097-2111. DOI: https://doi.org/10.1002/joc.5320.

Ligneau, L.; Tilly, S.; Baraer, F.; Dubreuil, V.; Bonnardot, V.; 2020: Observatoire du changement climatique pour l'agriculture: résultats préliminaires en Bretagne. In: Bonnardot, V., H. Quénol (Eds). Changement Climatique et Territoires, 427-432. *AIC Proceedings Rennes*. LETG UMR 6554 CNRS, Rennes, France.

Ly, S.; Charles, C.; Dégre, A.; 2013: Different methods for spatial interpolation of rainfall data for operational hydrology and hydrological modeling at watershed scale: a review. *Biotechnologie, Agronomie, Société et Environnement*, 17, 392-406.

Malheiro, A. C.; Santos, J.A.; Fraga, H.; Pinto, J.G.; 2010: Climate change scenarios applied to viticultural zoning in Europe, *Climate Research*, 43 (3), 163-177. DOI: 10.3354/cr00918.

Mérot, P.; Dubreuil, V.; Delaye, D.; Desnos, D.; 2012: Changement climatique dans l'Ouest: Evaluation, impact, perceptions. *Presses Universitaires de Rennes*. Rennes (Espace et territoires), France.

Michelangeli, P.A.; Vrac, M.; Loukos, H.; 2009: Probabilistic downscaling approaches: Application to wind cumulative distribution functions. *Geophysical Research Letters* 36 (11) DOI: 10.1029/2009GL038401

Moriondo, M.; Jones, G.V.; Bois, B.; Dibari, C.; Ferrise, R.; Trombi, G.; Bindi, M.; 2013: Projected shifts of wine regions in response to climate change. *Climatic Change*, 119 (3-4), 825-839.

Moss, R. H.; Edmonds, J.A.; Hibbard, K.A.; Manning, M.R.; Rose, S.K.; van Vuuren, D.P.; Carter, T.R.; Emori, S.; Kainuma, M.; Kram, R.; Meehl, G.; Mitchell, J.F.; Nakicenovic, N.; Riahi, K.; Smith, S.J.; Stouffer, R.J.; Thomson, A.M.; Weyant, J.P.; Wilbanks, T.; 2010: The next generation of scenarios for climate change research and assessment', *Nature*, 463 (7282), 747-756. DOI: 10.1038/nature08823.

Nabat, P.; Somot, S.; Cassou, C.; Mallet, M.; Michou, M.; Bouniol, D.; Decharme, B.; Drugé, T.; Roehrig, R.; Saint-Martin, D.; 2020: Modulation of radiative aerosols effects by atmospheric circulation over the Euro-Mediterranean region, *Atmospheric Chemistry* and *Physics* 20, 8315-8349, DOI: 10.5194/acp-20-8315-2020.

Neethling, E.; Barbeau, G.; Bonnefoy, C.; Quénol, H.; 2012: Change in climate and berry composition for grapevine varieties cultivated in the Loire Valley. *Climate Research*, 53 (2), 89-101. DOI: 10.3354/cr01094

Nesbitt, A.; Kemp, B.; Steele, C.; Lovett, A.; Dorling, S., 2016: Impact of recent climate change and weather variability on the viability of UK viticulture – combining weather and climate records with producers' perspectives. *Australian Journal of Grape and Wine Research*, 22 (2), 324-335. DOI: 10.1111/ajgw.12215

Nesbitt, A.; Dorling, S.; Lovett, A.; 2018: A suitability model for viticulture in England and Wales: opportunities for investment, sector growth and increased climate resilience, *Journal of Land Use Science*, 13 (4), 414-438. DOI: 10.1080/1747423X.2018.1537312

Nesbitt, A.; Dorling, S.; Jones, R.; 2019: Climate resilience in the United Kingdom wine production sector: CREWS-UK. *BIO Web of Conferences*, Les Ulis, Vol. 15, (2019). DOI: 10.1051/bioconf/20191501011

Ollat, N.; Touzard, J.-M.; van Leeuwen, C.; 2016: Climate change impacts and adaptations: new challenges for the wine industry. *Journal of Wine economics* 11, 1-11.

Parker, A. K.; Garcia de Cortázar-Atauri, I.; Chuine, I.; Barbeau, G.; Bois, B.; Boursiquot, J.-M.; Cahurel, J.Y.; Claverie, M.; Dufourcq, T.; Gény, L.; Guimberteau, G.; Hofmann R. W.; Jacquet, O.; Lacombe, T.; Monamy, C.; Ojeda, H.; Panigai, L.; Payan, J.C.; Rodriguez, B.; Rouchaud, E.; Schneider, C.; Spring, J.L.; Storchi, S.; Tomasi, D.; Trambouze, W.; Trought, M.; van Leeuwen, C.; 2013: Classification of varieties for their timing of flowering and veraison using a modelling approach: a case study for the grapevine species *Vitis vinifera* L. *Agricultural and Forest Meteorology*, 180, 249-264. DOI: 10.1016/j.agrformet.2013.06.005

Parker, A.; Schulmann, T.; Sturman, A.; Agnew, R.; Zawar-Reza, P.; 2014: Grapevine phenology of the Marlborough region, New Zealand. Available at: https://ir.canterbury.ac.nz/handle/10092/10543 (Accessed: 8 April 2021).

Parker, A.K.; Garcia de Cortázar-Atauri, I.; 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), 206-2016. doi: 10.1111/j.1755-0238.2011.00140.x.

Parker, A. K.; García de Cortázar-Atauri, I.; Gény, L.; Spring, J.-L.; Destrac, A.; Schultz, H.; Molitor, D.; Lacombe T.; Graça A.; Monamy C.; Stoll M.; Storchi P.; Trought M., Hofman, R.W.; van Leeuwen C.; 2020a: Temperature-based grapevine sugar ripeness modelling for a wide range of *Vitis vinifera* L. cultivars, *Agricultural and Forest Meteorology*, (107902), 1-13.

Parker, A.K.; Garcia de Cortazar-Atauri, I.; Trought, M.C.T.; Destrac, A.; Agnew, R.; Sturmann, A.; van Leeuwen, C.; 2020b: Adaptation to climate change by determining grapevine cultivar differences using temperature-based phenology models. *OENO One,* **54,** 954-977. DOI: 10.20870/oeno-one.2020.54.4.3861

Petitjean, T.; Tissot, C.; Thibault, J.; Rouan, M.; Quénol, H., Bonnardot, V.; 2022: Evaluation spatio-temporelle de l'exposition au gel en régions viticoles traditionnelle (Pays de Loire) et émergente (Bretagne). In Proceeding of *35th international congress of the Association Internationale de Climatologie*, Météo-France Toulouse 2022: http://www.meteo.fr/cic/meetings/2022/aic/

Quénol, H.; 2014: Changement climatique et terroirs viticoles. *Lavoisier Tec&doc*, 460. Available at: https://hal.archives-ouvertes.fr/hal-00992444 (Accessed: 3 April 2021).

Rauhut Kompaniets, O.; Nilson, H.; 2020: Wine tourism in southern Sweden. Opportunities and challenges. *Proceedings of the 2nd international Research Workshop on Wine Tourism: Challenges, Innovation and Futures*, 67-77, online.

Remenyi, T. A.; Rollins, D. A.; Love, P. T.; Earl, N. O.; Bindoff, N. L.; Harris, R. M. B.; 2020: Australia's wine future-A Climate Atlas. University of Tasmania, Australia. https://eprints.utas.edu.au/32250/

Ribes, A.; Boé, J.; Qasmi, S.; Dubuisson, B.; Douville, H.; Terray, L.; 2022: An updated assessment of past and future warming over France based on a regional observational constraint. *Earth System Dynamics*, 13, 1397-1415. DOI: 10.5194/esd-13-1397-2022

Saindrenan, G.; 2011: La vigne et le vin en Bretagne: chronique des vignobles armoricains origines, activité, disparitions et réussites, du finistère au pays nantais. Coop Breizh éd., France.

Santos, J.; Malheiro, A.; Pinto, J.; Jones, G.; 2012: Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. *Climate Research*, 51 (1), 89-103. DOI: 10.3354/cr01056

Soubeyroux, J.-M.; Bernus, S.; Corre, L.; Gouget, V.; Kerdoncuff, M.; Somot, S.; Tocquer, F.; 2020: Le nouveau jeu de simulations climatiques régionalisées sur la France pour le service DRIAS, 637-642. In: Bonnardot, V., H. Quénol (Eds). *Changement Climatique et Territoires*. *AIC Proceedings Rennes*, LETG UMR 6554 CNRS, Rennes, France.

Spellman, G.; 1999: Wine, weather and climate. *Weather*, 54 (8), 230-239.

Tilly, S.; 2019: Le programme ORACLE-observatoire régional sur l'agriculture et le changement climatique- valorisation des premiers résultats en région Bretagne. *Mémoire Master2 GAED-ETA*, Université Rennes 2, France.

Tonietto, J.; Carbonneau, A.; 2004: A multicriteria climatic classification system for grape-growing regions worldwide, *Agricultural and Forest Meteorology*, 124, 81-97. DOI: 10.1016/j.agrformet.2003.06.001

van Leeuwen, C.; Seguin, G.; 2006: The concept of terroir in viticulture. *Journal of wine research*, 17 (1), 1-10.

van Leeuwen, C.; Destrac-Irvine, A.; Dubernet, M.; Duchêne, E.; Gowdy, M.; Marguerit, E.; Pieri, P.; Parker, A.; de Rességuier, L.; Ollat, N.; 2019: An update on the impact of climate change in viticulture and potential adaptations. *Agronomy*, 9 (9), 514. DOI: 10.3390/agronomy9090514

Webb, L.; Whetton, P.; Barlow, E.; 2007: Modelled impact of future climate change on the phenology of winegrapes in Australia. *Australian Journal of Grape and Wine Research*, 13, 165-175.

Webb, L.; Whetton, P.; Barlow, E.; 2008: Climate change and winegrape quality in Australia. *Climate Research*, 36, 99-111. DOI: 10.3354/Cr00740.

Winkler, A. J.; Cook, J.A.; Kliewer, W.M.; Lider, L.A.; 1974: General viticulture. *University of California Press*, Berkeley Los Angeles, USA.

www.drias-climat.fr; 2021: *DRIAS, Les futurs du climat – Accompagnement*. Available at http://www.drias-climat.fr/accompagnement/sections/60

Zavlyanova, M.; 2020: Faisabilité climatique de la viticulture en Bretagne dans le contexte du changement climatique: spatialisation d'indices bioclimatiques et identification des régions viticoles potentielles. **Master Thesis**. Bordeaux Sciences Agro.