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ORIGINAL RESEARCH ARTICLE

Future climatic conditions may threaten adaptation capacities for vineyards along Lake Neuchâtel, Switzerland

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ABSTRACT

In Switzerland, as elsewhere in the world, climate change is challenging viticulture. Knowledge of the potential impacts is essential for preparing adaptation measures. Two aspects directly impacted by increasing temperatures are the choice of grapevine varieties and the location of vineyards. To help address these impacts, we analysed future trends in two bioclimatic indices, average growing season temperature (GST) and Huglin's heliothermal index (HI), in the Swiss canton of Neuchâtel. We conducted our analysis based on regional climate change scenarios referring to the emission pathways RCP4.5 and RCP8.5. Under the assumption of RCP8.5, trends in GST and HI indicate that the climate in this region will become too hot for most grapevine varieties currently cultivated, especially Pinot noir. Moreover, adaptation problems under RCP8.5 are expected to originate from an increase in climate extremes in both temperature and precipitation. Results based on RCP4.5 indicate a broader scope for adaptation, as the climate will remain suitable for a larger number of grapevine varieties within the current altitudinal limits of the Neuchâtel vineyards. In theory, an altitudinal shift of Pinot noir would also be possible under this emission pathway. In practice, however, the possibility of establishing vineyards above 600 m would be limited by the presence of protected forests and rocky areas. Our results highlight that vineyards in this region will need important adaptation measures if anthropic greenhouse gas emissions do not decrease rapidly and considerably, limiting the global temperature increase to < 1.5 °C.

KEYWORDS: bioclimatic index, climate adaptation, climate change, regional climate model, viticulture suitability

INTRODUCTION

Centuries of selection and experimentation by winegrowers have resulted in thousands of grapevine varieties cultivated in well-adapted wine regions (Huglin, 1978; Moriondo *et al.,* 2013; Unwin, 2005). In addition to climatic parameters, other elements of the terroir play an important role in the production of high-quality wine (Bonfante and Brillante, 2022). These include soil factors (soil type, texture and depth), physiological factors (leaf/canopy area, canopy evapotranspiration and rooting depth), cultural and oenological practices (cover crop management and irrigation), and their interactions (Bonfante *et al.,* 2017; Bramley *et al.,* 2011; Brillante *et al.,* 2018; Huglin and Schneider, 1998; Spangenberg and Zufferey, 2018; van Leeuwen and Seguin, 2006).

Nevertheless, climate, in particular temperature, remains the most important factor determining the geography of wine-producing regions and the choice of wine varieties (Huglin and Schneider, 1998; Jones, 2007), and it has been anticipated that grapevines will be among the plants most impacted by global warming (Jones and Webb, 2010). The rise in air temperature is expected to induce increasingly early phenological stages of grapes in spring and early summer (Cook and Wolkovich, 2016; Duchêne and Schneider, 2005; Fraga *et al.,* 2017; Jones and Webb, 2010; Laget *et al.,* 2008; Molitor and Junk, 2019). With harvests taking place earlier in a warmer climate, the typicity of wines is also likely to be affected in vineyards around the world (Jones and Webb, 2010; Spayd *et al.,* 2002; van Leeuwen and Darriet, 2016). The sugar level and potential alcohol content of wines are anticipated to increase, while the total acidity of grape berries and wines is expected to decrease (Battaglini *et al.,* 2009; De Orduña, 2010; Laget *et al.,* 2008; Schultz, 2000). Warmer conditions are also likely to alter other aromatic and phenolic elements (De Orduña, 2010; Dequin *et al.,* 2017).

Beyond the rise in air temperature, climate change also involves an increase in solar radiation and in heatwave frequency and duration in Western Europe, increasing the risk of sunburn to grapevines (IPCC, 2021; Sgubin *et al.,* 2018; Stock *et al.,* 2005). Temperatures above 35 °C can be particularly problematic for the cultivation of vines, regardless of the grape variety, especially if they occur on consecutive days as a heat wave (Kliewer, 1977; Spayd *et al.,* 2002). The simultaneous increase in heat waves and drought could induce more frequent physiological disorders, such as berry shrivelling and xylem embolism formation in some grape varieties (Lovisolo *et al.,* 2008; Zufferey *et al.,* 2011; Zufferey *et al.,* 2022). Climate change will also lead to changes in rainfall regime, intensifying climatic demand and water deficits during the growing season, with impacts on phenology and on grape and wine quality (van Leeuwen *et al.,* 2009; Zufferey *et al.,* 2017). Finally, hailstorms may cause considerable losses in European vineyards, and an increase has been observed in the frequency and intensity of hail and rainstorm events during the last decades (IPCC, 2021; Raupach *et al.,* 2021).

Short-term adaptation strategies consist of changes to cultural and vinification practices. The vineyards currently situated in the warmest areas and without possibilities of altitudinal shifts will probably disappear progressively in the coming decade if other adaptation solutions are not found (Morales-Castilla *et al.,* 2020; Moriondo *et al.,* 2013; Stock *et al.,* 2005). It is also likely that viticulture will witness altitudinal and latitudinal shifts in the cultivated grape varieties (Fraga *et al.,* 2012; Jones, 2007). The northern limits of current viticultural areas in the Northern Hemisphere will probably move further northward, and the cultivation of high-quality wines is expected to expand into more northern latitudes (Doutreloup *et al.,* 2022; Jones *et al.,* 2022; Morales-Castilla *et al.,* 2020; Nesbitt *et al.,* 2022).

Adaptation strategies will be key to the success of vineyards in the future. It is possible to adapt on a short- or medium-term basis by changing the genetic material (rootstocks and clone types) of the cultivated grape varieties, the water regime (e.g., installation of irrigation systems), and the cultivation practice and vine care (e.g., agroforestry, canopy management and late pruning; (van Leeuwen and Destrac-Irvine, 2017; van Leeuwen *et al.,* 2009). Winemaking techniques, e.g., to decrease the alcohol content, are another adaptation possibility (Dequin *et al.,* 2017; Tilloy *et al.,* 2015). As site conditions in vineyards vary at the local scale, adaptation measures may vary at this scale as well (Quénol *et al.,* 2019). There are indeed important meso and microclimatic disparities at the local scale between the vineyards most exposed to higher temperatures, i.e., at low altitude, with a southern orientation, and on the edge of a lake, and areas that were formerly less suitable for viticulture, i.e., areas less exposed to sun or bowl-shaped.

In viticulture, adaptation decisions need to be made at an early stage, as the plants need three to four years of growth before the first production, and the lifespan of established vineyards is a few decades. Specific information on climate change and its effects on grapevines at the regional scale is, therefore, essential for guiding adaptation. In this context, it is worth noting that several bioclimatic indices have been developed to characterise the link between climate and vineyards and to define the conditions and suitability for vine growing. Examples of such indices are the Winkler index (WI), Huglin's heliothermal index (HI), Cool night index (CI), and other growing degree day indices (GDDs) (Jones *et al.,* 2005; Tonietto and Carbonneau, 2004). Two such indices are considered in the present study. The first is the average growing season temperature (GST), an index that can be used to analyse the potential suitability of terroir to different grape varieties using air temperature alone (Jones *et al.,* 2005; OIV, 2012). The second is Huglin's heliothermal index (HI), which is highly correlated with an adequate sugar level at harvest (Huglin and Schneider, 1998) and may indicate the optimum cultivation conditions for various grape varieties.

Intended as an extension of a previously published study (Comte *et al.,* 2022), the overall goal of this study is to examine future trends in GST and HI in the canton of

Neuchâtel, a region of Switzerland where the total wine cultivation area is small but where viticulture has a long tradition and represents an important pillar of the agricultural sector. On the one hand, we analyse the evolution of thermal conditions at a representative weather station for Neuchâtel, discussing in detail the implications of the resulting trends for the choice of varieties. On the other hand, we present GST and HI maps targeting the two periods 2035–2064 and 2070–2099. The maps illustrate the geographic implications of increasing temperatures for the wine cultivation zones of the canton of Neuchâtel during the 21st century.

In Switzerland, temperatures have been rising twice as fast as the global average (CH2018, 2018; Rebetez and Reinhard, 2008). Swiss vineyards have generally benefited from climate change until now, as Switzerland is located near the cooler limit of vine growing (Zufferey *et al.,* 2022). Wine quality has been improving over the last decades (thanks to an increased maturity of some varieties, especially the late ones), there is more diversity in grape varieties, and the harvests are more regular (Zufferey *et al.,* 2022). Swiss wine regions commonly experience spring frost, but this risk does not appear to be increasing below 800 m a.s.l. (Vitasse and Rebetez, 2018; Vitasse *et al.,* 2018).

In addition to observed weather data covering 1971–2020, we base our analysis on an ensemble of climate change scenarios developed for Switzerland by the National Centre for Climate Services (NCCS), which is available to researchers as the so-called CH2018 scenarios (CH2018, 2018). The CH2018 scenarios refer to three different emission pathways: the Representative Concentration Pathways (RCP) 2.6, 4.5 and 8.5 (Meinshausen *et al.,* 2011). Here we limit our attention to RCP4.5 and RCP8.5, the two scenarios involving the most significant changes in thermal conditions.

MATERIALS AND METHODS

1. Bioclimatic indices

As mentioned above, we adopted the average growing season temperature (GST; Jones *et al.* (2005)) and Huglin's heliothermal index (HI; (Huglin and Schneider, 1998)) to gauge the impact of climate change on the conditions for wine cultivation. For locations in the Northern Hemisphere, GST is defined as the daily mean temperature (T_{mean}) between 1 April and 31 October:

$$GST = \frac{1}{214}\sum_{01.04}^{31.10} T_{mean}$$

HI is defined as

$$HI = k\sum_{01.04}^{30.09}\left(\frac{T_{mean}+T_{max}}{2} - 10\right)$$

where, as before, T_{mean} is the daily mean temperature, T_{max} is the daily maximum temperature, and k (~ 1.05 for Neuchâtel) is a factor that depends on latitude.

For both indices, a generic classification of current grapevine varieties has been proposed in relation to GST (Jones *et al.* (2005) and to HI (Huglin and Schneider, 1998) Table 1).

2. Study area

The study area includes the vineyard region along the edge of Lake Neuchâtel in Switzerland (Figure 1). All vineyards are located below 600 m a.s.l. (Figure 1). Neuchâtel vineyards (about 600 ha) have historically been located in a cool climate region in terms of the growing season temperature (13 to 15 °C) and in a very cool climate in terms of HI (<1500). Pinot noir (55 %) and Chasselas (27 %) are the main grape varieties of these vineyards. The vineyards of Neuchâtel lie on a bedrock of yellow Jura limestone, covered in part by more or less compact glacial moraine. However, Pinot noir is generally found on more sandy soils than those with Chasselas. Most of the vines are pruned in simple Guyot.

3. Data

For our analysis, we used daily minimum (T_{min}) and maximum (T_{max}) air temperature. Data covering the recent decades were obtained from the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss, 4 stations; https://gate.meteoswiss.ch/idaweb/), a network of proprietary agrometeorological

TABLE 1. Climatic classes for Huglin's heliothermal index and average growing season temperature

Very cool <1500	None	None	None
Cool 1500–1800	Muller-Thurgau, Blauer Portugieser, Pinot blanc, Pinot gris, Aligoté, Gamay noir, Gewürztraminer, Pinot noir, Riesling, Chardonnay, Sylvaner, Sauvignon blanc, Melon	Cool 13–15 °C	Muller-Thurgau, Gamay, Pinot gris, Gewurtzraminer, Riesling, Pinot noir, Chardonnay
Temperate 1800–2100	Cabernet Franc, Blaufrankisch, Chenin blanc, Cabernet, Merlot, Sémillon, Riesling, Ugni blanc	Intermediate 15–17 °C	Riesling, Pinot noir, Chardonnay, Sauvignon blanc, Sémillon, Cabernet Franc, Tempranillo, Merlot, Malbec, Syrah, Dolcetto, Viognier
Temperate warm 2100–2400	Grenache, Syrah, Cinsaut, Carignan, Aramon	Warm 17–19 °C	Sauvignon blanc, Sémillon, Cabernet Franc, Tempranillo, Dolcetto, Merlot, Malbec, Viognier, Syrah, table grapes, Cabernet-Sauvignon, Sangiovese, Grenache, Carignan, Zinfandel, Nebbiolo, raisins
Warm 2400–3000	None	Hot 19–22 °C	table grapes, raisins
Hot >3000	None		

*Climate optimum for different grape varieties for two bioclimatic indices: Huglin's heliothermal index (HI) and average growing season temperature (GST). Adapted from (Jones, 2006) and (Huglin and Schneider, 1998).

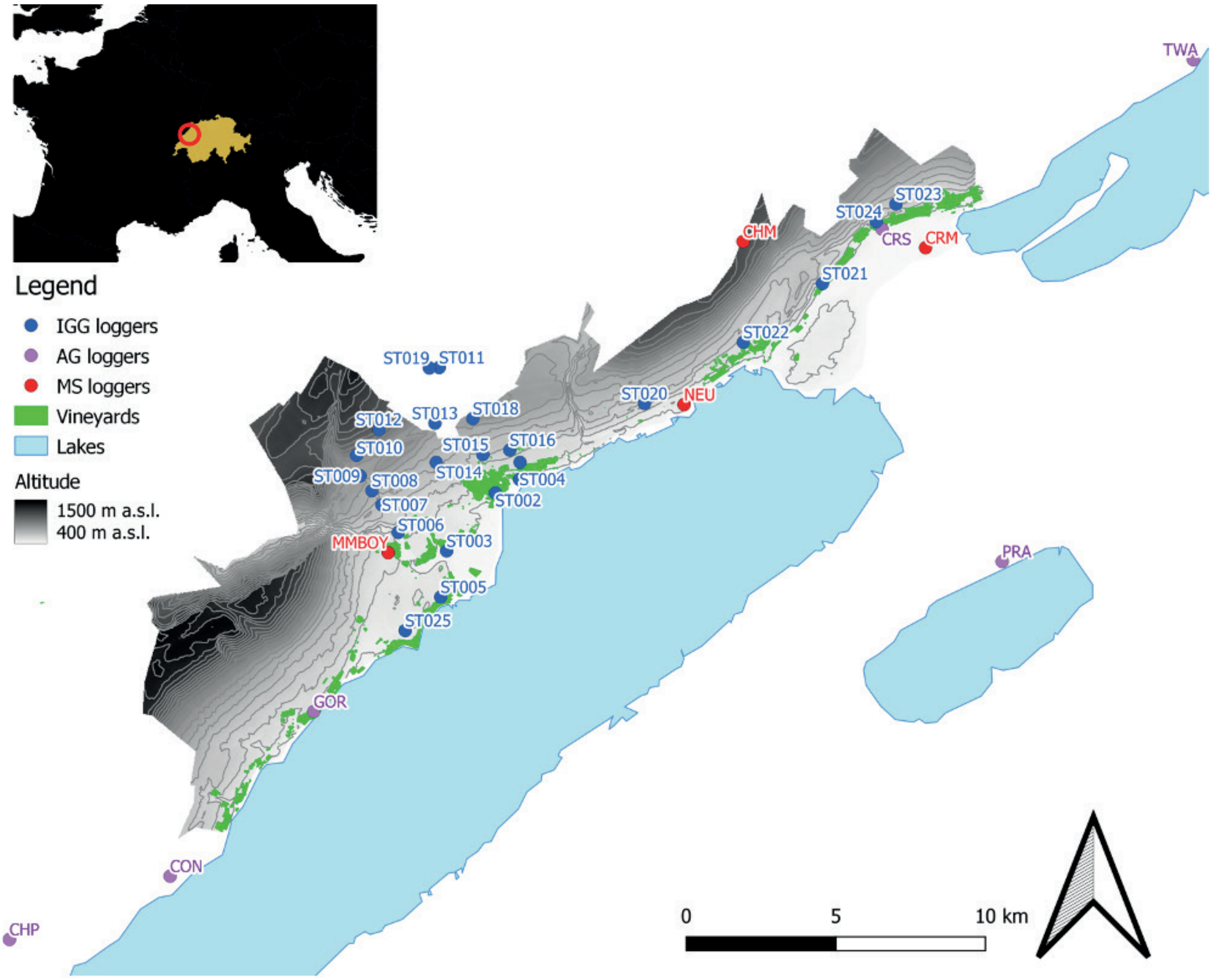

FIGURE 1. Locations of Neuchâtel vineyards and of the air temperature loggers.

IGG loggers are our own, AG loggers are from Agroscope, and MS loggers are from MeteoSwiss. Precise logger coordinates (longitude, latitude and altitude) are detailed in the Supplementary Material. Acronyms: IGG = Institut de Géographie, University of Neuchâtel; AG = Agrometeo; MS = Swiss Federal Office of Meteorology and Climatology (MeteoSwiss); ST = station.

stations (Agrometeo, 6 stations; http://www.agrometeo.ch/fr/meteorology/datas), and 25 of our own temperature loggers recording air temperature (°C) at 2 meters above the ground. We systematically used homogenised data from MeteoSwiss when available. Most of the Agrometeo loggers and our own loggers are located within the study area, but four of them (TWA, PRA, CHP, CON) are located outside the perimeter of the study, yet in similar conditions and in vineyards areas. The temperature loggers produced an average lapse rate for the vineyard region, which explained 97 % of the observed regional temperature variability (Comte *et al.,* 2022).

To simulate future trends in the selected bioclimatic indices, we used the local scenarios for the Neuchâtel station available from the repository maintained by NCCS (CH2018, 2018). The Neuchâtel station (NEU) used in the CH2018 dataset is located at 485 m a.s.l. and is representative of the average climate of the Neuchâtel vineyards (Comte *et al.,* 2022). The data repository includes downscaled data for a range of GCM-RCM chains from EURO-CORDEX, and it provides daily temperature data (T_{min}, T_{mean} and T_{max}) for main MeteoSwiss stations (CH2018, 2018). For the emission pathways, we selected the widely used RCP4.5 and RCP8.5 scenarios (Pachauri *et al.,* 2014). The number of individual model chains used in our study was 17 for RCP4.5 and 22 for RCP8.5. For developing GST and HI maps, we focused on a single model chain, namely SMHI-RCA4 ECEARTH EUR11, which is representative of the ensemble scenarios (CH2018, 2018).

4. Methods

As a first stage, we considered, for each RCP, the full ensemble of available CH2018 scenarios for discussing the overall evolution in GST and HI up to the end of the current century. For illustrative purposes, we filtered the time series using a Kolmogorov–Zurbenko filter (Zurbenko and Smith, 2018), and we used the filtered time series to assess the exceedance probability for given GST and HI thresholds. This step was meant to translate the "time of emergence" (Hawkins and Sutton, 2012) into a "time of action", i.e., to determine the time when a switch in grapevine varieties is likely to become a must rather than a choice.

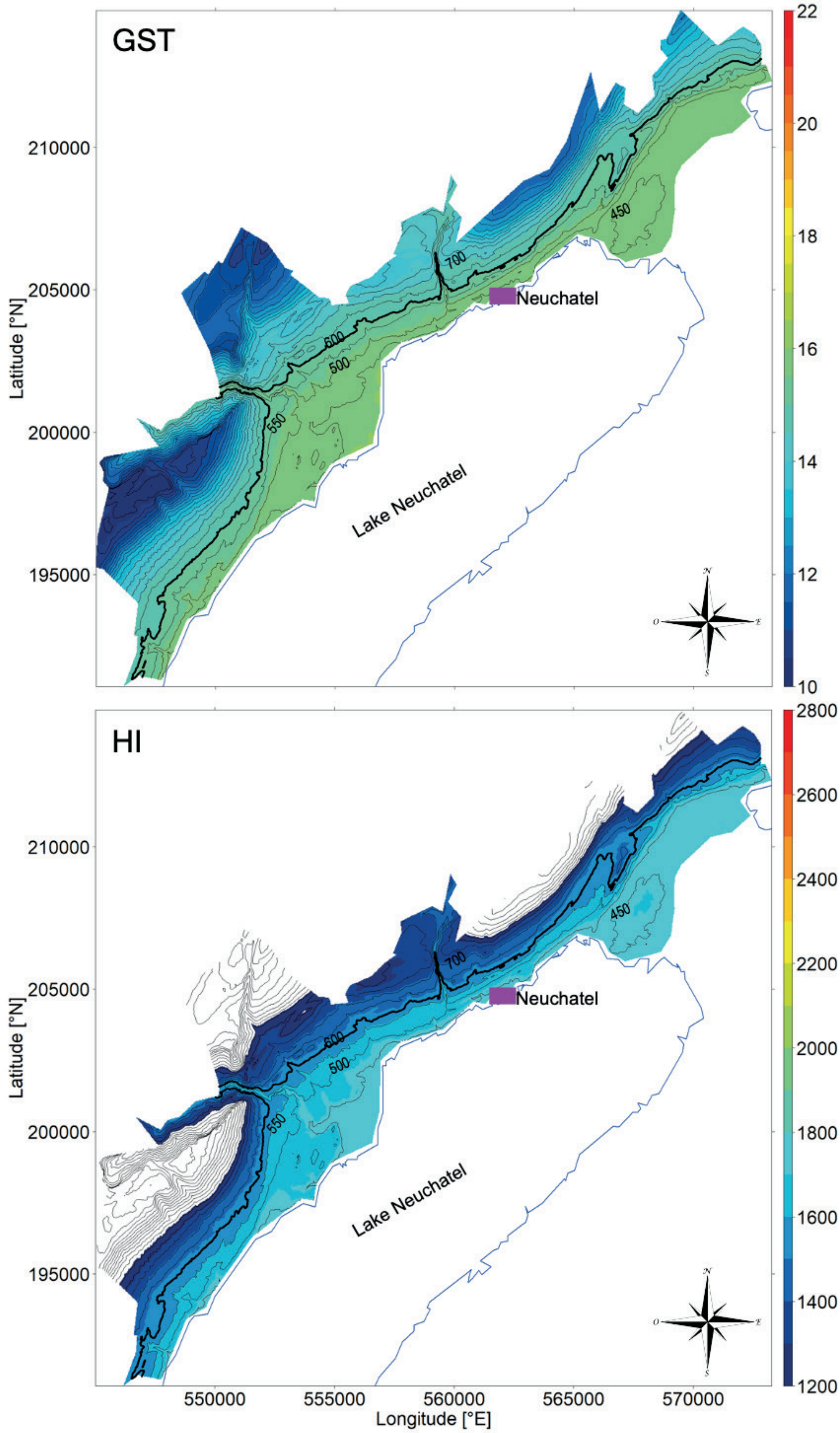

FIGURE 2. Average growing season temperature (GST) and Huglin's heliothermal index (HI) in Neuchâtel vineyards during the period 1991–2020.

The bold black line indicates the altitudinal limit of the vineyards (600 m a.s.l.). Longitude and latitude are given according to the Swiss reference system CH1903 (EPSG:21781).

In the second stage, we examined in more detail the evolution of thermal conditions at the Neuchâtel weather station, limiting the focus to the SMHI-RCA4 ECEARTH EUR11 model chain. For discussing the trends, we refer to the climatic classes proposed by Jones (2006) and by Huglin and Schneider (1998) as shown in Table 1.

Finally, we used this same model chain to construct GST and HI maps valid for 2035–2064 and 2070–2099. The maps illustrate the regional GST and HI patterns within the littoral region borders of the canton of Neuchâtel around the middle and end of the present century, providing a basis for discussion of the regional suitability of future conditions for grapevine cultivation. We developed the maps following the approach described in detail in Comte *et al.* (2022), i.e., using the adiabatic lapse rate average per month to project the results obtained for the Neuchâtel weather station onto a high-resolution digital elevation model, making use of the Swiss reference geodetic system (CH1903, EPSG:21781). Referring to Comte *et al.* (2022), we note that the adiabatic lapse rates explain 97 % of the temperature variations within the Neuchâtel wine country.

All analyses were performed using the R statistical software, version 4.1.1 (R Core Team, 2019).

RESULTS

1. Current climate of Neuchâtel vineyards

In terms of GST, the climate characterising the Neuchâtel vineyards was intermediate during the period 1991–2020, with temperatures ranging from 16 °C along the edge of the lake to 15.1 °C at the highest altitudes (Figure 2). HI ranged from 1750 along the edge of the lake to 1560 at higher altitudes. Referring to Huglin and Schneider (1998), the climate of Neuchâtel vineyards was cool to temperate during this period.

2. Trends in GST and HI with RCP4.5 and RCP8.5 with all RCMs

The long-term evolution of GST and HI at the MeteoSwiss NEU station from 1980 to 2099, with RCP4.5 and RCP8.5 and all the available RCMs of the CH2018 dataset, is shown in Figure 3. The filtered data show that not all RCMs are able to reproduce the trend observed over 1980–2020 (Figure 3). A notable exception is RCM SMHI-RCA4-ECEARTH EUR11 (SRE-KZ), which simulates the observed trend accurately (Figure 3). Until the middle of the 21st century, the RCMs do not show important differences between RCP4.5 and RCP8.5.

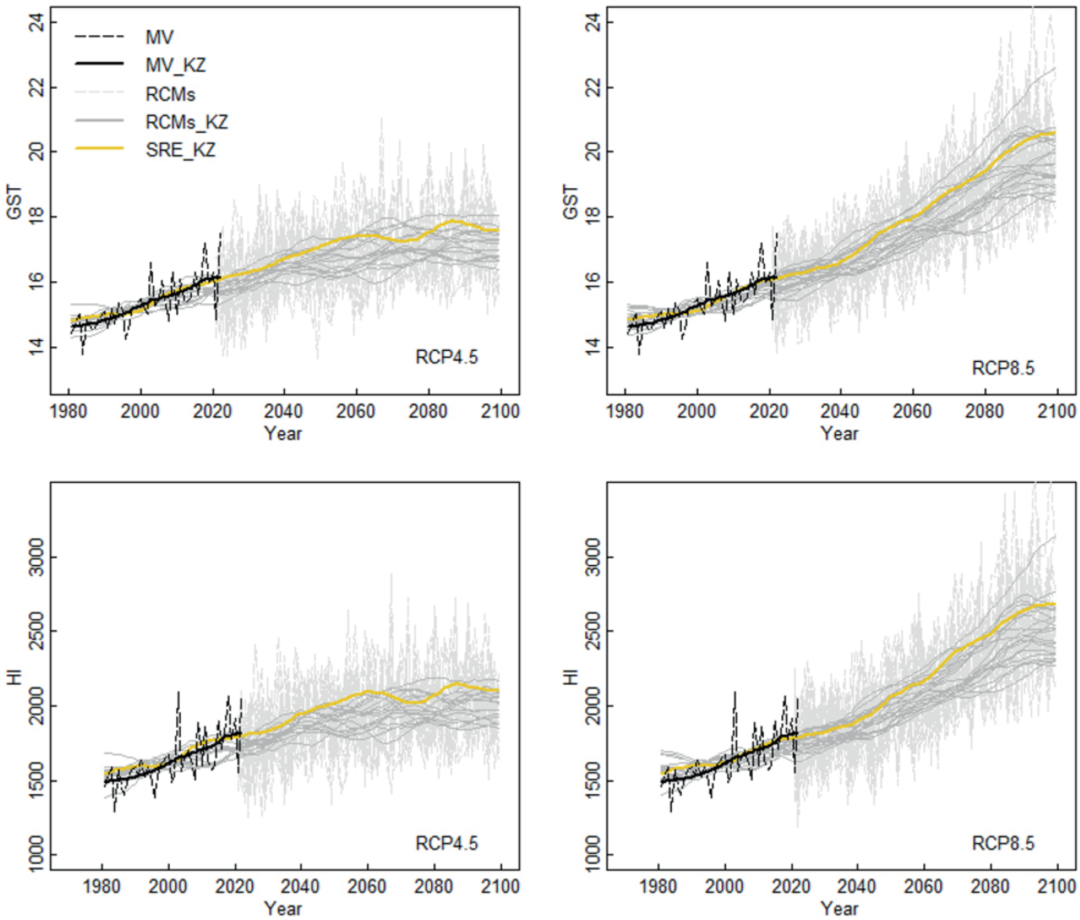

FIGURE 3. Trends in average growing season temperature (GST) and Huglin's heliothermal index (HI) with all available data of the CH2018 dataset with RCP4.5 and RCP8.5.

MV are measured values, KZ is the Kolmogorov–Zurbenko filter, RCMs are the CH2018 regional climate model data, and SRE is the RCM SMHI-RCA4-ECEARTH_EUR11.

With respect to the classification indicated in Table 1, more than half of the model chains indicate a GST above 17 °C (transition from intermediate to warm conditions) by 2070 with RCP4.5, but already by 2049 with RCP8.5 (Figure 4). Under RCP8.5, all models indicate a GST above 17 °C by the end of the century. Concerning the 19 °C threshold (transition between warm and hot conditions), only a few models indicate its exceedance with RCP4.5, while with RCP8.5, more than half of the models suggest its exceedance after 2082 (Figure 4).

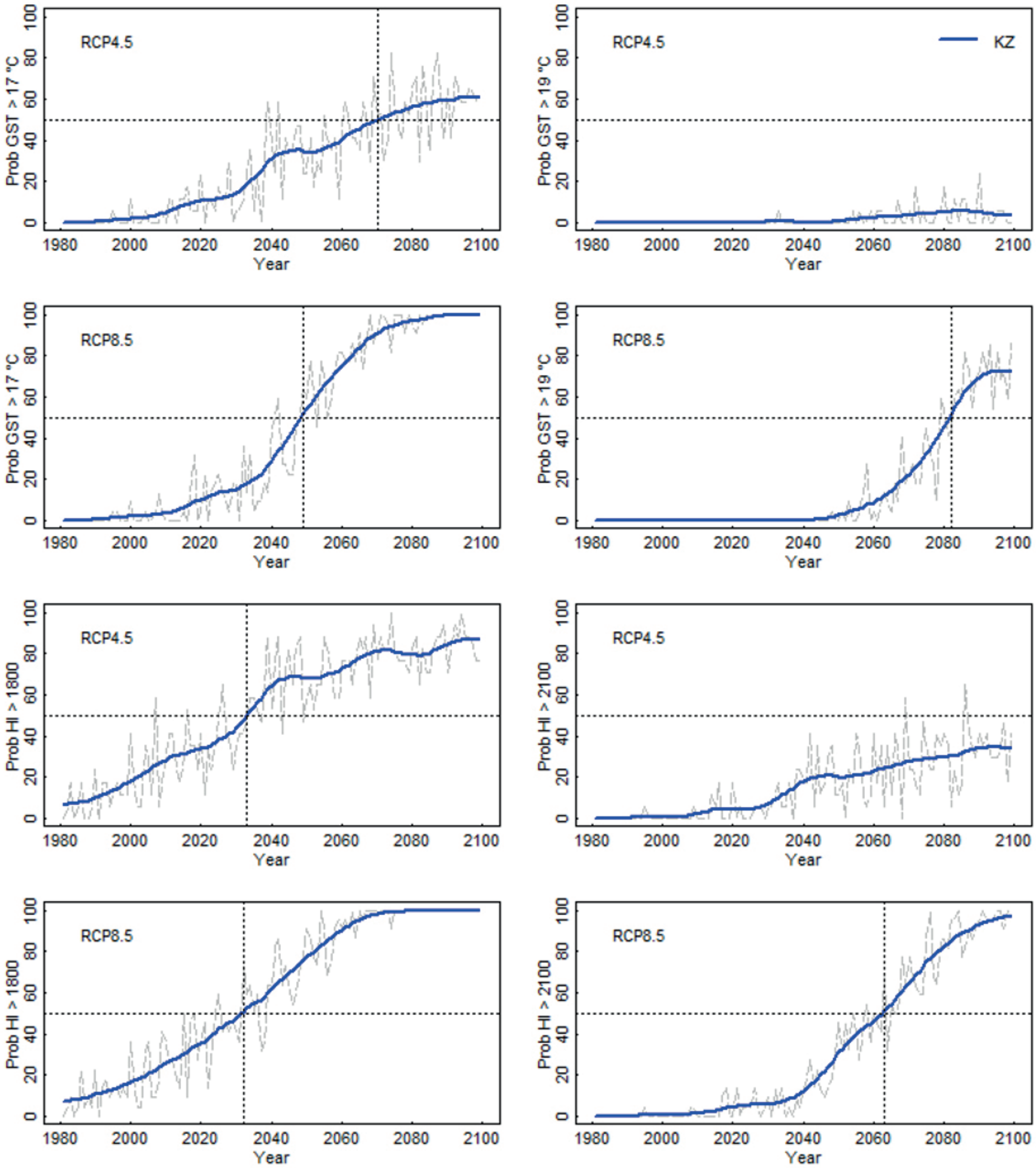

FIGURE 4. The probability that the growing season temperature (GST) exceeds 17 °C (two first panels on the top left) or 19 °C (two panels on the top right), and Huglin's heliothermal index (HI) exceeds 1800 (two panels on the bottom left) or 2100 units (two panels on the bottom right).

The probability is computed for each year considering the number of model chains indicating an exceedance of the given threshold divided by the total number of chains included in the ensemble. The blue lines are a filtered version of the raw estimates obtained by applying a Kolmogorov–Zurbenko filter (filter length = 11 years, 2 iterations).

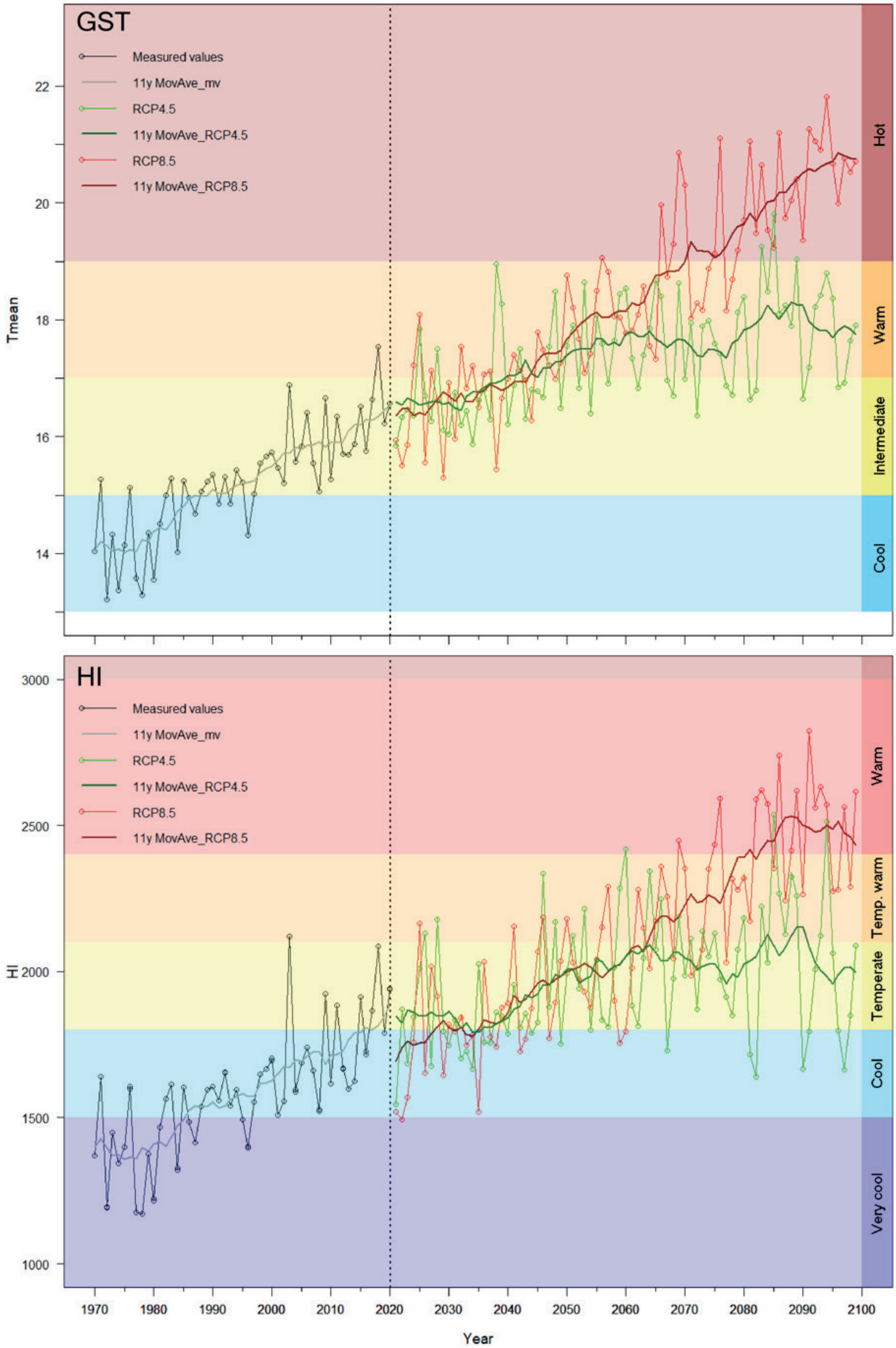

FIGURE 5. Trends in average growing season temperature (GST) and in Huglin's heliothermal index (HI) at the Neuchâtel weather station from 1970 to 2099. Grey circles indicate measured values from 1970 to 2020.

Green circles and red circles indicate simulated values under RCP4.5 and RCP8.5, respectively. Eleven-year moving averages are shown as thick solid lines in the corresponding colours. The coloured bands in the background indicate vineyard climate types according to the classifications by Jones (2006) and Huglin and Schneider (1998).

Regarding HI, exceedance of the 1800 threshold (transition from cool to intermediate conditions) is indicated by more than half of the models after 2033 with RCP4.5 and after 2032 with RCP8.5 (Figure 4). Exceedance of the 2100 HI threshold is very unlikely under RCP4.5, but at least half of the models based on RCP8.5 suggest this possibility after 2063.

3. Future bioclimatic conditions of Neuchâtel with a focus on SMHI-RCA4-ECEARTH_EUR11

The long-term evolution of GST and HI at the NEU station from 1980 to 2099, with the SMHI-RCA4-ECEARTH EUR11 RCM under RCP4.5 and RCP8.5, is shown in Figure 5 Large differences are apparent between RCP4.5 and RCP8.5 for both GST and HI Regarding GST, the climate classification shifts from "intermediate" to "warm" by 2040 (Figure 5). With RCP8.5, it shifts to "hot" by 2070 (Figure 5). Regarding HI, there is a gap between the measured and predicted values with both RCP4.5 and RCP8.5 (Figure 5). This suggests that even this model may slightly underestimate the projections. HI values already shifted from "very cold" to "cold" between 1970 and 2015. Since then, they have shifted to the "temperate" classification. Our results indicate that the classification would remain the same in the future under RCP4.5 but with values in the upper part of the classification starting in 2050. Some years would, therefore, belong to the "warm temperate" classification due to interannual variability. With RCP8.5, the classification would become, on average, "warm temperate" by 2060. It would even shift to the "warm" classification by 2080.

The linear trends for three periods (Table 2) illustrate the difference between RCP4.5 and RCP8.5 given by the 11-year moving average (Figure 5). The trends in GST and HI are more than 1.5 times higher for RCP8.5 (+0.56 GST and +116 HI per decade) than for RCP4.5 (+0.32 GST and +76.5 HI per decade) during 2035–2064. As RCP4.5 is based on a drastic decrease in global annual greenhouse gas emissions by 2040 and a stabilisation of the concentrations by approximately 2060, no upward trend in GST or HI is observed with this scenario for the period 2070–2099 (Table 2 and Figure 5). Under RCP8.5, the upward trend is significantly steeper for the period 2070–2099 than for 2035–2064 for GST (+0.78 GST per decade) but not for HI (+124.3 HI per decade).

4. GST maps for mid-century and for the end of the century with RCP4.5 and RCP8.5

The area of the current vineyards (430 to 580 m a.s.l.) is, on average, classified as "warm" for the period 2034–2065 with both scenarios. GST ranges from 17.9 °C (430 m a.s.l.) to 17 °C (580 m a.s.l.) with both RCP4.5 and RCP8.5 (Figures 6 and 8), corresponding to an increase of 1.9 °C between the two time periods. No significant difference in GST appears between the periods 2035–2064 and 2070–2099 with RCP4.5

The differences between RCP4.5 and RCP8.5 are more pronounced for the period 2070–2099. With RCP4.5, GST varies from 18 °C at lower altitudes to 17.1 °C at higher altitudes, i.e., 580 m a.s.l. (Figures 6 and 8). With RCP8.5, GST varies between 20.2 °C and 19.3 °C (Figures 6 and 8).

With RCP4.5, the corresponding current viticultural climate conditions (Figure 2) would be located above 650 m a.s.l. in 2035–2064 and also in 2070–2099. With RCP8.5, the corresponding current conditions would again be above 650 m a.s.l. in 2035–2064 but would be above 1200 m a.s.l. in 2070–2099 (Figures 6 and 8).

5. HI maps for mid-century and for the end of the century with RCP4.5 and RCP8.5

For 2035–2064, the current vineyards lie, on average, in climate conditions classified as "intermediate" with both scenarios, and HI values vary between 2100 at the edge of the lake and 1900 at higher altitudes with both RCP4.5 and RCP8.5 (Figures 7 and 8).

There is no significant difference in HI between the 2035–2064 and 2070–2099 periods with RCP4.5 (Figures 5 and 6).

The differences between RCP4.5 and RCP8.5 are more pronounced for the period 2070–2099 than for 2035–2064 (Figures 7 and 8). At the end of the century, HI values vary between 2160 at the edge of the lake and 1960 at higher altitudes with RCP4.5, and between 2620 and 2420 with RCP8.5 (Figures 7 and 8), i.e., conditions classified as "warm" by Huglin and Schneider (1998).

With RCP4.5, the HI conditions that currently characterise vineyards (Figure 2) would be located above 700 m a.s.l. in 2035–2064 and also in 2070–2099. With RCP8.5, the corresponding current conditions would again be above 700 m a.s.l. in 2035-2064 but would be above 1100 m a.s.l. in 2070-2099 (Figures 7 and 8).

TABLE 2.

Data	Period	Trend in GST (per decade)	Trend in HI (per decade)
Measured values	1990–2019	0.52 ± 0.1***	101.9 ± 28.5**
RCP4.5	2035–2064	0.32 ± 0.16*	76.5 ± 35.5*
RCP4.5	2070–2099	None	None
RCP8.5	2035–2064	0.56 ± 0.12***	116 ± 31.9***
RCP8.5	2070–2099	0.78 ± 0.17***	124.3 ± 37.2**

*Linear trends in GST and HI for the NEU station at mid-century (2035–2064) and at the end of the century (2070–2099) under RCP4.5 and RCP8.5. *** = $p < 0.001$, ** = $p < 0.01$ and * = $p > 0.05$.

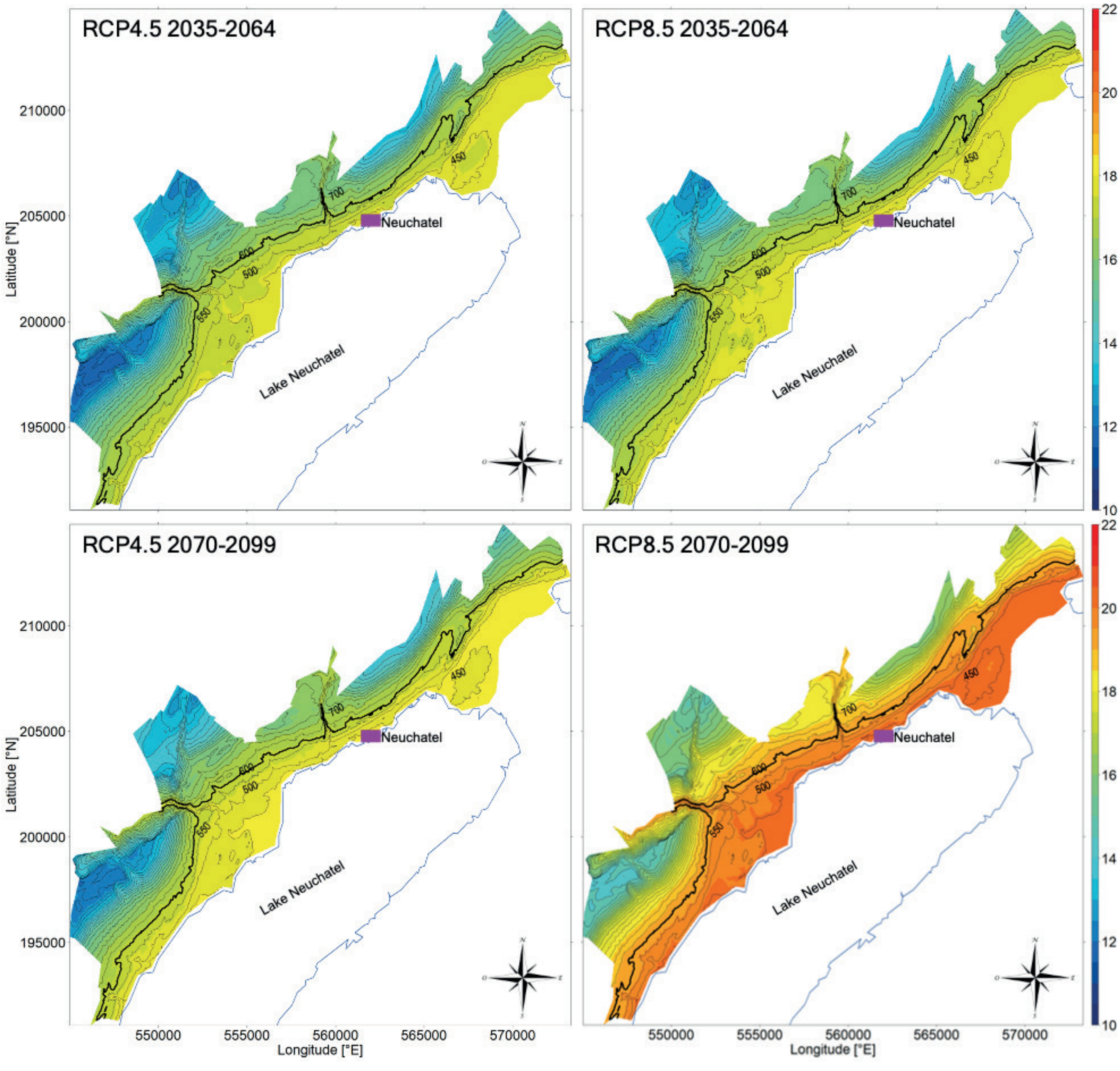

FIGURE 6. Predicted average growing season temperature (GST) for 2035–2064 and 2070–2099 with RCP4.5 and RCP8.5.

The bold line indicates the altitudinal limit of the current vineyards (600 m a.s.l.). Longitude and latitude are given according to the Swiss reference system CH1903 (EPSG:21781).

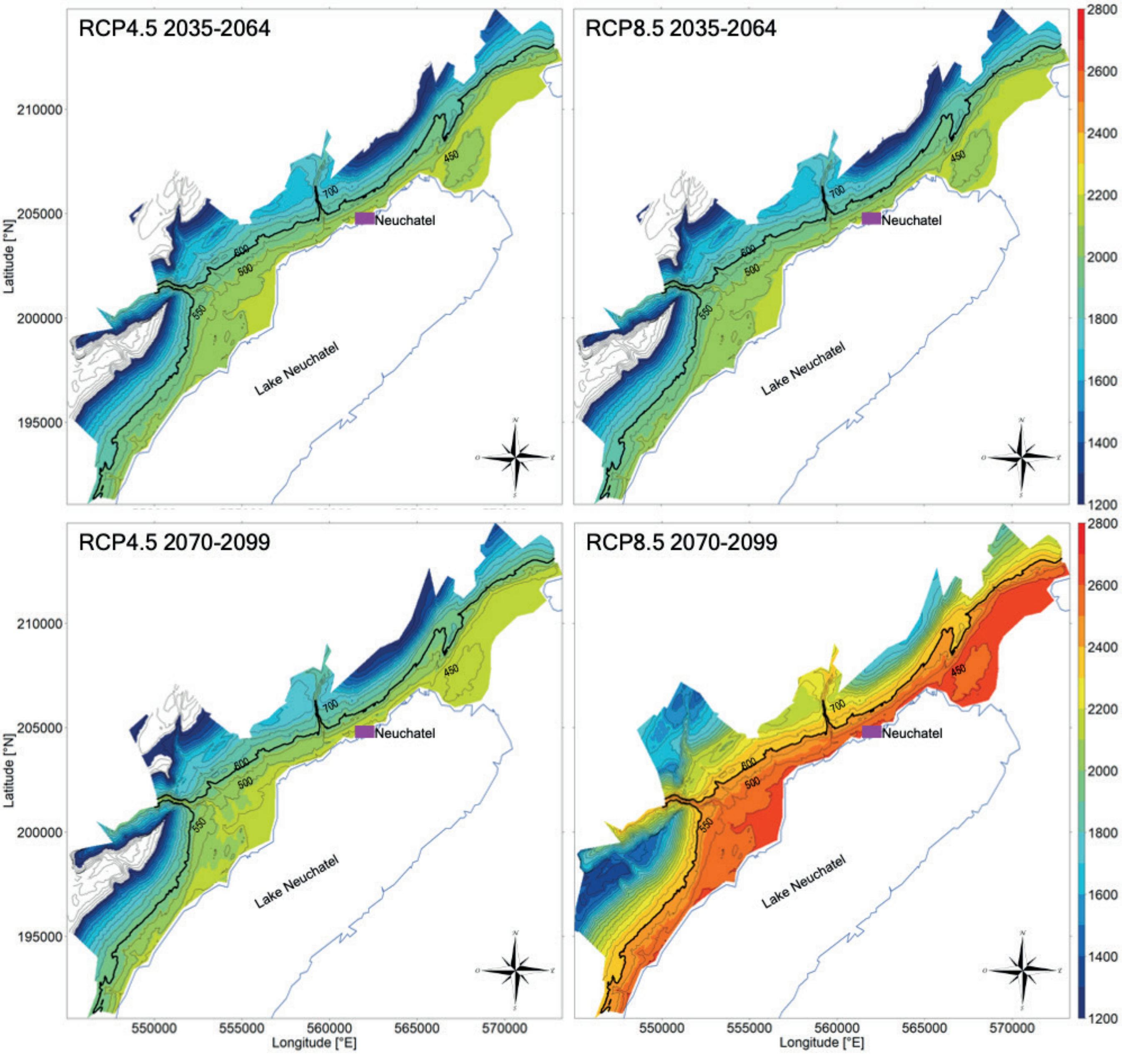

FIGURE 7. Predicted Huglin's index (HI) values for the 2035–2064 and 2090–2099 periods with RCP4.5 and RCP8.5. The bold line indicates the altitudinal limit of the current vineyards (600 m a.s.l.). Longitude and latitude are given according to the Swiss reference system CH1903 (EPSG:21781).

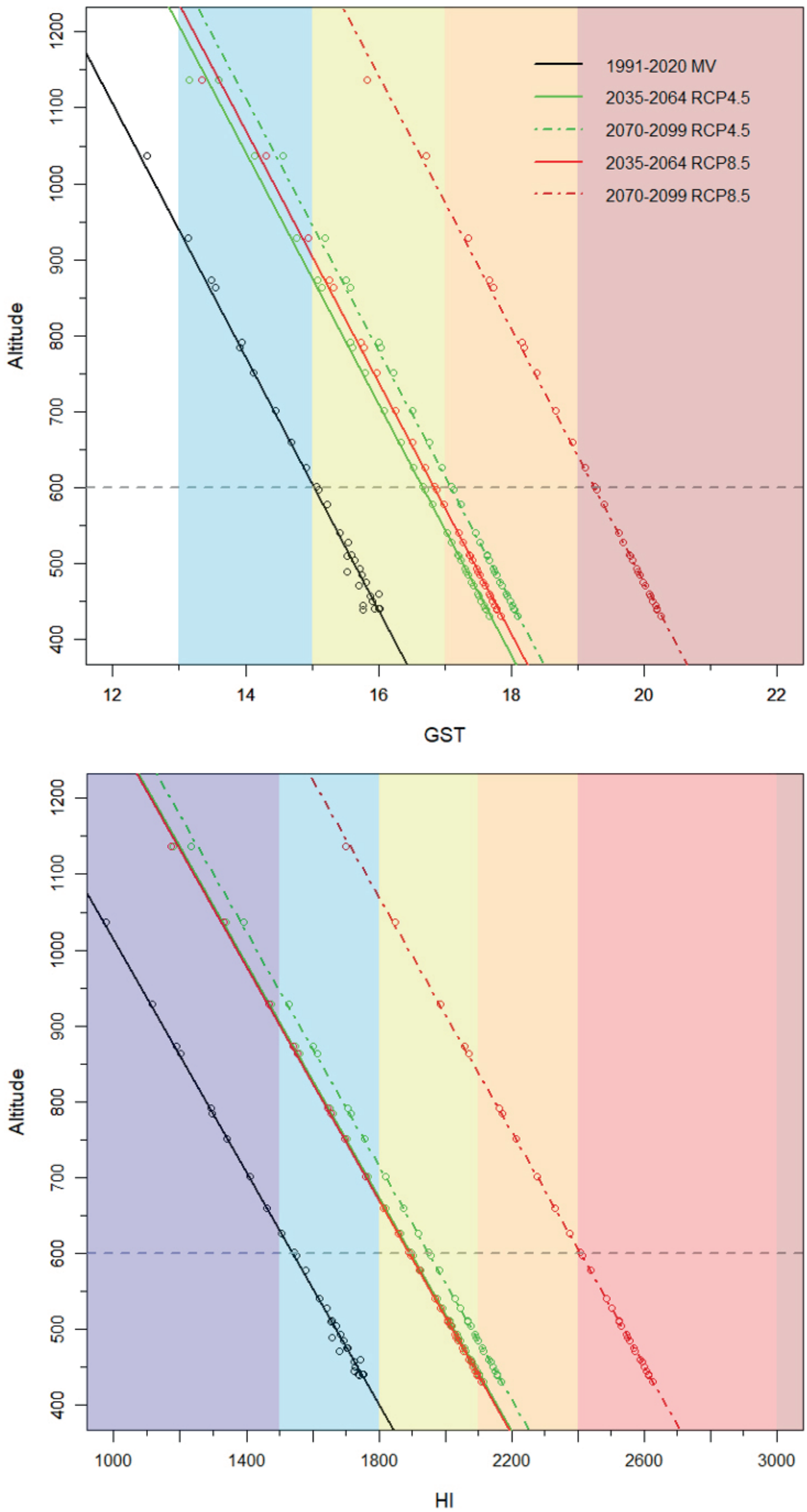

FIGURE 8. Average growing season temperature (GST) and Huglin's heliothermal index (HI) as a function of altitude for three periods (1991–2020, 2034–2064 and 2070–2099) with RCP4.5 and RCP8.5.

The dotted grey line indicates the current altitudinal limit of vineyards (600 m a.s.l.). The coloured bands correspond to the same classifications as shown in Figure 2. MV indicates measured values.

DISCUSSION

Our analyses of observed and expected trends for the two bioclimatic indices HI and GST indicate that, regardless of which climate scenario unfolds, the vineyards of Neuchâtel will face climatic conditions during the next decades that will require adaptation measures. Actually, GST is already reaching the upper limit for Pinot noir in the generic classification proposed by Jones (2006). Similarly, HI is already slightly above the optimum defined by Huglin and Schneider (1998) for this variety. Until mid-century (2035–2064), our results show relatively similar future climate prospects for RCP4.5 and RCP8.5. In contrast, our results indicate that towards the end of the century, vineyards in the current cultivation areas of Neuchâtel would be characterised by a new climate under RCP8.5 only: hot and humid during the vegetation period with frequent extreme events. The Neuchâtel vineyards will have to cope with longer and more intense periods of drought, as well as more frequent intense precipitation events.

To interpret our results, a probable underestimation of the current warming by the available model chains must be taken into account. We have underlined the gap observed between the measured data and those predicted with all RCMs of the CH2018 dataset with respect to the historical period 1970–2020, which is particularly evident for HI but also occurs for GST. For decades, temperatures have been consistently increasing more than expected by the latest IPCC reports, i.e., reality has regularly surpassed model predictions. Other authors have also shown that the increase in summer temperature is underestimated by most of these models. For example, Boé *et al.* (2020) and Schwingshackl *et al.* (2019) noted that most general circulation models (GCMs), as well as RCMs, tend to underestimate the real increase occurring in summer temperatures in Europe, especially in terms of daily maxima. It is, therefore, likely that the actual temperature trends will be steeper than those resulting from our analyses. In fact, our results show that only three model chains satisfactorily replicate actual temperature trends: SMHI-RCA4 ECEARTH EUR11, SMHI-RCA4 HADGEM EUR11, and SMHI-RCA4 CCCMA EUR11. In terms of future warming, SMHI-RCA4 HADGEM EUR11 and SMHI-RCA4 CCCMA EUR11 are at the upper end of the range of future temperature projected by the ensemble of the CH2018 models, while SMHI-RCA4 ECEARTH EUR11 is more representative of the ensemble media. -

Temperature is an extremely important parameter for vineyards, but other criteria also play a role in the production of high-quality wines, including soil characteristics, water availability (vine water status) and evapotranspiration. The response of vines and their ability to adapt to new environmental constraints (e.g., warming and drought) will depend to a large extent on the interactions between soil, climate and grape variety. Soil characteristics, particularly the capacity of the soil to function as a water reserve during the growing season and drought episodes, will be essential to ensure the growth, yield and quality of the grapes. The management of soil maintenance (e.g., type of grass cover and percentage of soil covered with grass) will play a key role in the consumption and availability of soil water reserves during the hot and dry parts of the season.

The risks of water and mineral competition between grasses and vines will become a major issue for winegrowers with increasing global warming. The cultivation techniques that mitigate these risks lie in the choice of plants (grape varieties and rootstocks) adapted to the characteristics of the terroir, in the reduction of leaf area, in the reduction of the grassy area between the rows of vines in case of drought, and in rational irrigation as a last resort. Wine growers will also have to take into account the fact that the advance in the phenological stages of the grape varieties traditionally grown in Neuchâtel will have an impact on wine typicity even if the same varieties, such as Pinot noir, are still grown.

While adaptation solutions to climate change regarding cultural and vinification practices, such as drip irrigation, late winter pruning, and a reduced leaf-to-fruit ratio, could be used by wine growers in the short term, switching grape varieties and an altitudinal shift for the less thermophilic varieties are the main long-term solutions if scenarios such as RCP8.5 unfold. If it is theoretically possible to move part of a vineyard to a higher altitude, spring frost must also be taken into account, as moving farther away from the moderating effect of the lake involves a greater risk. This risk could be minimised by planting varieties with a later phenology. This solution is also limited in practice by the fact that around Neuchâtel, most of the land above 600 m a.s.l. is covered by protected forests or by other cropland, where the soils may not be suitable for viticulture.

CONCLUSIONS

Our analyses show that, with both the RCP4.5 and RCP8.5 climate scenarios, future climatic conditions will need adaptation measures for viticulture in the region of Neuchâtel to continue, particularly if winegrowers intend to maintain present varieties, typically Pinot noir. Both bioclimatic indices applied here, i.e., GST and HI, suggest that the areas currently used for vine growing around Neuchâtel will be more appropriate for grape varieties such as Merlot, Viognier, Cabernet Franc, Malbec and Syrah than for Pinot noir in the mid-century (2035–2064). However, although these temperature classes, developed by research and widely adopted for vine growing, have largely been proven valid, the temperature is not the only determining factor to be considered for the adaptability of grape varieties. Specifically, water availability will become a challenge in our study region, whereas it never was in the past, and thus, irrigation systems are not available. The implementation of adaptation measures, such as irrigation systems and agroforestry, should make it possible to maintain the production of high-quality Pinot noir. Still, the wine typicity will change, and this parameter will have to be taken into account in decisions concerning future customers' tastes.

For the second half of the century, our results show continuing significant increases in the bioclimatic indices with RCP8.5 but no significant increase in either index with RCP4.5. With RCP8.5, the climate at the end of the century is expected to be too hot for vine cultivation in the region of Neuchâtel, even for southern grape varieties, meaning that adaptation for wine growers is expected to be very difficult. With RCP8.5, there would be a HI difference of 400 in just 30 years. This implies that changes in climate would be so fast that it would become increasingly complicated to choose which grape variety to grow.

Solutions to rapid climate warming, mainly moving part of the vineyards to higher altitudes, will have to be considered but will need to take into account various limits: increased risk of spring frost and the fact that most of the land above the current vineyard's altitudes is unsuitable for viticulture. Finally, the choice between vineyards and other cropland as the surfaces devoted to agriculture become smaller will potentially become increasingly difficult.

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