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ORIGINAL RESEARCH ARTICLE

Climate change is likely to favour insect pest species in mid-latitude vineyards: the case study of Neuchatel

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ABSTRACT

Climate change has major impacts on viticultural ecosystems worldwide, affecting wine production. Apart from direct impacts, the increase in temperature during the development season is likely to favour insect species, including polyvoltine ones, leading potentially to more damage in the vineyards. In this study, we examined the extent to which changes in mean temperature over the development season (March through September) can potentially increase the voltinism change the phenology and influence the reproduction of pest species in the vineyard area of Neuchatel (Switzerland). We first analysed long-term daily mean temperature data from 1970 to 2022 at the meteorological station of Neuchatel. Then we used two climate scenarios (RCP4.5 and RCP8.5) to analyse daily mean temperature during the period 2023–2099. For both of these periods, we computed the number of growing degree days (GDDs) above 10 °C, as it is the base development temperature for many polyvoltine pest species. We then used specific bioclimatic models for two major pest species, namely the European grapevine moth (*Lobesia botrana*) and the American grapevine leafhopper (*Scaphoideus titanus*) to compare the current and future suitability of these two species to the air temperature conditions in Neuchatel. Our results show an increase of about 425 GDDs since 1970 (+85 GDDs per decade). According to our models, values will continue to rise during the next decades, with a trend ranging from +28 GDDs per decade (RCP4.5) to +100 GDDs per decade (RCP8.5). This could lead to additional generations of polyvoltine pest species. A third annual generation can be expected in one year out of four for the European grapevine moth by the middle of the 21st century. While temperature conditions are currently moderately favourable for the American grapevine leafhopper, they are predicted to become highly favourable by the middle and the end of the century under both scenarios. These trends mean that climate change is likely to increase pest damage risks in the vineyards of Neuchatel in the future. Pest regulation will remain crucial in limiting major impacts on wine production.

KEYWORDS: climate change, development season, growing degree day, *Lobesia botrana*, *Scaphoideus titanus*, vine pest

INTRODUCTION

Climate change is a major issue for vine-growing, as grapevine is particularly sensitive to local climatic conditions (Jones, 2006; Jones and Davis, 2000; van Leeuwen *et al*., 2004). It has direct impacts on the plants and on the quality of wine, such as an increase in the sugar level and potential alcohol concentration of wines, a decrease in the total acidity of wines, and shifts in the phenological stages of grapes (Jones and Webb, 2010; Spayd *et al*., 2002). Extreme events, such as hailstorms, spring frost, heavy precipitation and heat waves, can reduce wine production. Climate change also impacts vine-growing indirectly by affecting vineyard ecosystems, for example, the interactions between species. Insect pests are particularly important, as they can strongly reduce both the quantity and quality of grapes. All these impacts require climatic studies at the local scale to develop adaptation strategies in vineyard areas.

Climate change impacts the spatial distribution and activity of major vine pest insects (Boudon-Padieu and Maixner, 2007; Daane *et al*., 2018). As insects are ectothermic organisms, they are strongly sensitive to ambient temperature (Bale *et al*., 2002). In a temperate climate, it is likely that thermophile pest species will benefit from global warming (Schneider *et al*., 2023; Schneider *et al*., 2022). This includes polyvoltine species [*i.e*., species able to produce more than one generation per year; Altermatt (2010)], as well as invasive exotic species which are likely to spread poleward (Yan *et al*., 2017). A warmer development season is likely to increase voltinism and favour exotic species. This could lead to more damage to forests and crops, including vineyards. Therefore, it is crucial to study how temperature conditions during the development season are changing and to understand their potential impacts on pest populations.

In a temperate climate, an increase in voltinism is associated with both a warmer and a longer development season. Warmer springs induce an earlier start of the first generation and of other phenological events (Forrest, 2016). An increase in voltinism, including in pest species, is associated with warmer conditions allowing them to complete full or partial additional cycles. The impact of climate change on voltinism has already been observed for some butterfly species across Europe since the 1980s (Altermatt, 2010). Additional generations have also been noticed for some pest species in Switzerland. For example, the spruce bark beetle (*Ips typographus*) has been able to produce three generations per year instead of two since the 2000s on the Swiss Plateau (Jakoby *et al*., 2022). Similarly, a second generation has been observed for the first time during the exceptionally warm year 2018 for the marmorated stink bug [*Halyomorpha halys*; Stoeckli *et al*. (2020)], as well as since the 2010s for the box tree moth [*Cydalima perspectalis*; Nacambo *et al*. (2014)]. Both of these species are invasive, originating from warmer climates. In general, it is expected that species from more southern regions will reach Switzerland during the next decades, benefitting from milder winters (Schneider *et al*., 2021; Vittoz *et al*., 2013) and warmer development seasons. The predicted increase in voltinism and spread of invasive species are, therefore, likely to lead to more damage, including in vineyards.

In this study, we focused on the potential impacts of climate change on insect pests in the vineyard region of Neuchatel (Switzerland). Based on the literature, we identified two major pest species which are threatening vines, and for which thermal requirements are known. The European grapevine moth (*Lobesia botrana*) is a polyvoltine species already observed in the region, while the American grapevine leafhopper (*Scaphoideus titanus*) has not yet been observed in Neuchatel but is currently spreading across south-western Switzerland.

1. European grapevine moth

The European grapevine moth originates from Southeastern Europe and has been widespread in European vineyards (Benelli *et al*., 2023a), including in Switzerland, since at least the beginning of the 20th century (Castex *et al*., 2020). This pest currently produces two generations per year in Neuchatel, and up to four generations and a partial fifth per year in Spain (Gutierrez *et al*., 2018). Its base development temperature threshold (tb) was estimated at 10 °C by Gutierrez *et al*. (2018), while Briere and Pracros (1998) estimated it at between 8 °C and 12 °C depending on the stage of the life cycle. The number of GDDs per generation has been earlier estimated at 458 for tb = 10 °C (Touzeau, 1981). This can be explained by the fact that the larvae growing speed is influenced by the phenological stage and the variety of the grapes on which the larvae feed (Thiéry *et al*., 2014).

2. American grapevine leafhopper

The American grapevine leafhopper is an univoltine insect that originates from North America and is considered a major vineyard pest species, as it is the vector of the flavescence dorée disease (Linder *et al*., 2016). Nevertheless, population monitoring in cages in the 1980s in the south of France revealed a possible partial second generation for this insect (Chuche and Thiéry, 2014). This insect was first observed in France in 1958 (Bonfils and Schvester, 1960) and is now present in most of the major European wine countries (Chuche and Thiéry, 2014). In Switzerland, the American grapevine leafhopper was first detected in 1968 in Ticino (Baggiolini *et al*., 1968), and has already been detected more recently in Valais (Sneiders *et al*., 2019), and in the Lake Geneva basin (Schaerer *et al*., 2007).

This study aimed to determine the extent to which changes in the mean temperature during the development season could impact pest species in the vineyard region of Neuchatel. We first analysed trends in GDDs with tb = 10 °C, as this is the base development temperature for the European grapevine moth and other polyvoltine pest species (Schneider *et al*., 2023). In addition, growing degree-days base 10 °C is most common in grapevine (Jones and Davis, 2000). We used temperature data over the last 50 years (1970–2022) and two Representative Concentration Pathway (RCP4.5, RCP8.5) scenarios for the future (2023–2099). We then used specific bioclimatic models for the European grapevine moth

and the American grapevine leafhopper to compare the current and future suitability of these two species to the temperature conditions in Neuchatel. We focused our results on voltinism for the European grapevine moth, and on the viability of egg-laying for the American grapevine leafhopper.

MATERIALS AND METHODS

1. Study area

The study area was the vineyard region in the canton of Neuchatel, Switzerland (Figure 1). The vineyards are located on 600 hectares along the edge of Lake Neuchatel, from 430 to 580 m a.s.l (Figure 1). The main cultivated grape varieties are Pinot noir (presently 55 %) and Chasselas (27 %). Due to climate change, the vine climate of the region has already warmed from cool to temperate (Comte *et al*., 2022; Comte *et al*., 2023).

2. Data

We used data from MeteoSwiss (https://gate.meteoswiss.ch/idaweb/) for the past and present period (1980–2020), including homogenised data from the NEU station. The station is located in a grass and tree-covered area at an elevation corresponding to the Neuchatel vineyards (485 m a.s.l.) and is therefore representative of the climatic conditions of the vineyards in the area. For future simulations, we used data for the NEU station from the CH2018 programme (CH2018, 2018) and from two Representative Concentration Pathways (RCP4.5, RCP8.5). We selected data from the Regional Climate Models (RCM) *SMHI-RCA4-ECEARTH*, which is driven by the Swedish Meteorological and Hydrological Institute (SMHI) in the Euro-CORDEX project. The data have been obtained at the Swiss level by the National Center for Climate Services (NCCS). It is provided from the DAILY-LOCAL data of the CH2018 dataset (CH2018, 2018). Data was emulated from measured data and with climatic simulations from RCP4.5 and RCP8.5. The data of this RCM fit well with the historical data for the NEU station and the trends in various bioclimatic indices computed for the NEU station are near the average trends of all the 18 other RCMs available in the CH2018 dataset (Comte *et al*., 2023).

To produce bioclimatic maps, we used data from 35 stations originating from MeteoSwiss (MS, 4), Agrometeo (AG, 6) and our own loggers (IGG, 25) in the region (Table S1).

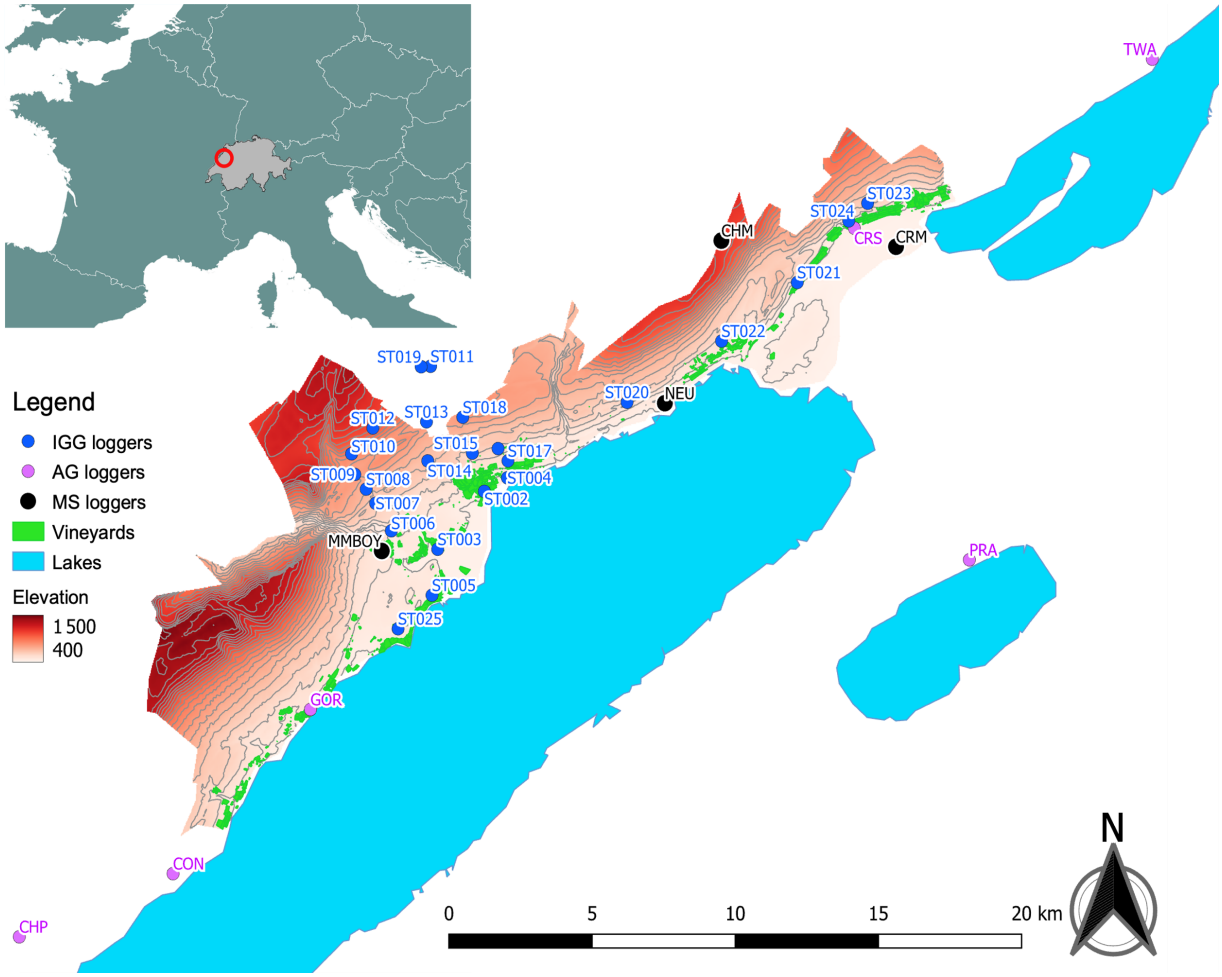


FIGURE 1. Locations of the Neuchatel vineyards considered in this study and of the air temperature loggers. IGG loggers are our own, AG are Agroscope loggers, and MS are MeteoSwiss loggers.

3. Methods

We based our analysis on daily mean temperature values (Tmean), defined as the mean of daily minimum and maximum temperature. We computed growing degree days (GDDs) using a threshold (tb) relevant to the development of the European grapevine moth: GDD = daily Tmean minus tb (in °C), where GDD = 0 when Tmean ≤ tb. We summed the GDD values over the year to compute annual GDDs (Tschurr *et al*., 2020). We determined linear trends for past and future periods (1970–2022 and 2023–2099). We also used 11-year moving averages.

3.1. GDD maps

We used the adiabatic lapse rate per month to downscale the temperature data from the MeteoSwiss weather station of Neuchatel to a high-resolution digital elevation model, using the method described by Comte *et al*. (2022). The lapse rates explain 0.97 % of the temperature variation along the edge of Lake Neuchatel, according to Comte *et al*. (2022).

3.2. Modelling the development of European grapevine moth

We used the Lobesia Generic Model developed by Castex *et al*. (2020) to compute the annual number of generations and the mean date of generation start of the European grapevine moth. This model is based on daily mean temperature and photoperiod, as it is known that photoperiod is an important driver for diapause and overwintering of the species (Benelli *et al*., 2023a; Castex *et al*., 2020).

3.3. Modelling the development of American grapevine leafhopper

We used a delta method similar to the method used by Sneiders *et al*. (2019) to compute simulated air temperatures for each hour of the day of the RCM. This method was adapted from Gago Da Silva *et al*. (2012). It is based on high-resolution RCM output and meteorological observations of the studied area and can be summarised as follows:

$$V = V_{obs} + \Delta$$

with

$$\Delta = \left(V_{sim,2} - V_{sim,1}\right) \times f_I + b$$

$V_{sim,2}$ corresponds to the perturbation in the future variable as predicted by the RCM; $V_{sim,1}$ is the current variable simulated by this same model for a given climate scenario; f_1 is a correction factor for global warming, and b corresponds to the noise. V, V_{obs}, and V_{sim} are surface variables (temperatures in the context of this work) in a space-time function (Gago Da Silva *et al*., 2012).

We calculated the American grapevine leafhopper's developmental degree days (DD) using the emulated hourly temperatures described above, and we estimated the development of this species according to the methodology described by Sneiders *et al*. (2019). We calculated DDs based on hourly temperatures (Bloesch and De Siebenthal, 1988). We added a lethal temperature $T_{let} \geq 40\,°C$ to these DDs. A 3-hour exposure to temperatures above 40 °C is expected to kill 50 % of adults and larvae (Rigamonti *et al*., 2011), whereas a 6-hour exposure to temperatures above 28 °C is expected to kill 50 % of eggs (Rigamonti *et al*., 2014). Fecundity is expressed as the number of potential eggs O and is a function of the daytime temperature from 08.00 to 18.00 T_{fec} based on data from (Rigamonti *et al*., 2017). A maximum egg production of 40 at 21 °C and 22 °C is given by the equation:

$$O = -0.7019 \times T_{fec}^2 + 30.2693 \times T_{fec} - 276.1067$$

We cross-referenced the emulated temperatures with information from the American grapevine leafhopper development models in Sneiders *et al*. (2019). We used this information to determine the potential number of eggs per female, defining three thresholds: not adapted = median number of eggs per female ≤ 10; adapted = median number of eggs per female between 10 and 40; and highly adapted = median number of eggs per female ≥ 40.

RESULTS

1. GDDs (tb = 10 °C) in Neuchatel vineyards

The average GDDs for the vegetation period in Neuchatel have increased by 84.9 per decade since 1970. For future periods (the present to the end of the 21st century), average GDDs for the vegetation period are predicted to increase by 27.7 (±8.6) for RCP4.5 and by 100.4 (±7.9) for RCP8.5.

For the last decades (1991–2020), the vine-cultivated area has ranged from 1300 GDDs at the edge of the lake to 1100 GDDs at the highest elevation of the vineyards (Figure 2a, Figure2b).

No significant difference in average GDDs for the vegetation period (April through September) is visible between RCP4.5 and RCP8.5 for the 2035–2064 period (Figures 2a and Figure 3). The vine-cultivated area (430 m to 580 m a.s.l.) is predicted to experience between 1450–1650 GDDs (RCP4.5) and 1500–1700 GDDs (RCP8.5) in this period (Figure 3). There is also no significant difference in average vegetation period GDDs visible between 2035–2064 and 2070–2099 (range 1550–1750) with RCP4.5 (Figure 3). The difference between RCP4.5 and RCP8.5 is more pronounced for the period 2070–2099. With RCP8.5, the vine-cultivated area will experience between 1900 and 2100 GDDs at the end of the century (Figure 3).

2. Climatic acclimatisation of the European grapevine moth in Neuchatel vineyards

While climatic conditions were not suitable for a third generation of the European grapevine moth during the last 30 years, our results show that they will become so for about one year out of four by the middle of the 21st century, with both RCP4.5 and RCP8.5 (Table 1). By the end of the century, this value could reach 40 % of the years with scenario RCP8.5, while it is not predicted to significantly change with RCP4.5 (Table 1).

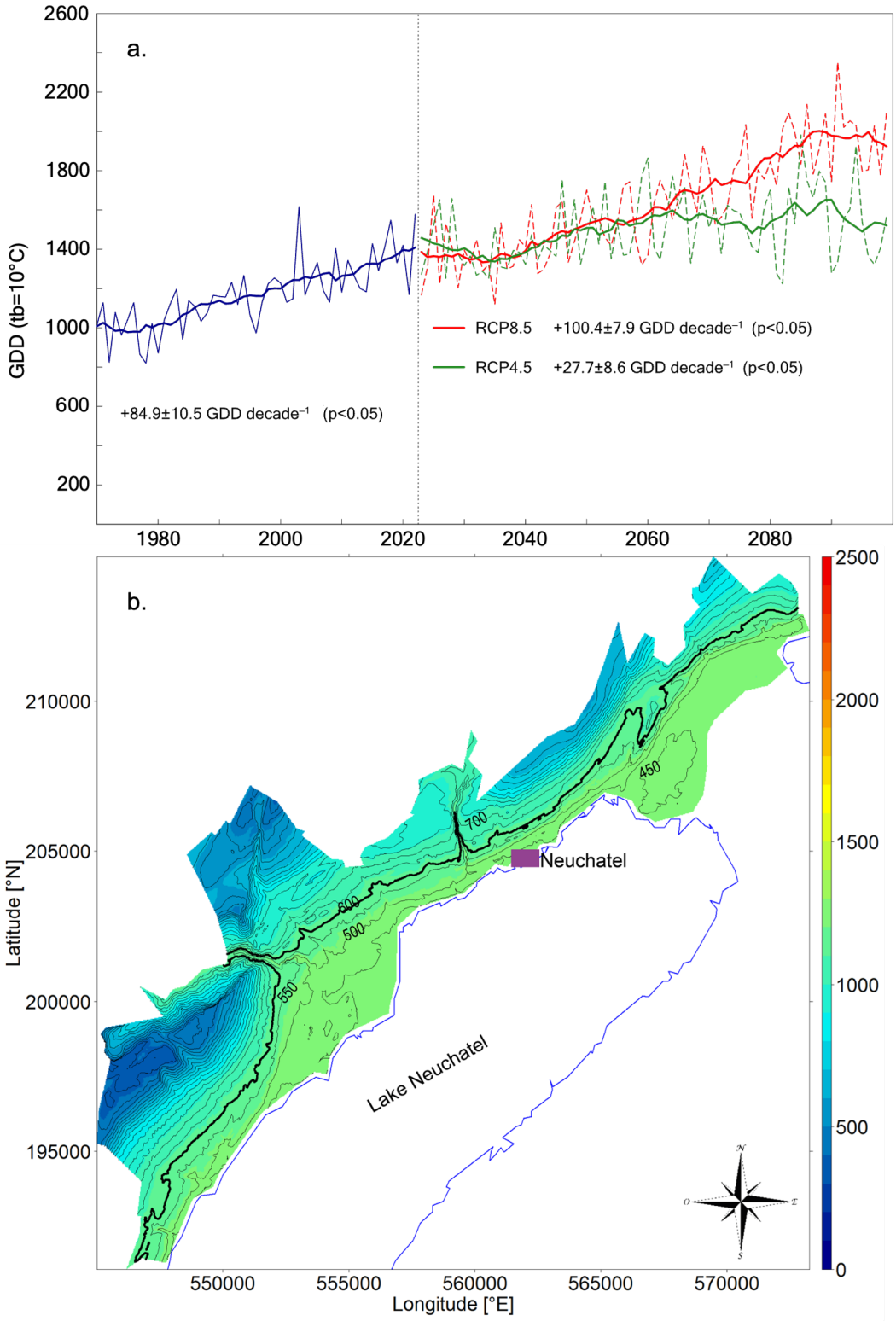


FIGURE 2. Growing degree days (GDDs; base development temperature threshold [tb] = 10 °C) at the MeteoSwiss climate station NEU for the past decades and for projections with Representative Concentration Pathway RCP4.5 and RCP8.5 (a). Annual GDDs measured (1970-2022, thin solid lines) and simulated under RCP4.5 and RCP8.5 (2023–2099, dashed lines). Eleven-year moving averages are shown as thick solid lines, and slopes (± SE) of the linear regressions are displayed. Average spatial distribution of GDDs (tb = 10 °C) for 1991–2020 (b). The bold black line in (b) indicates the current elevational limit of the vineyards (600 m a.s.l.). Scale of the figure: 550'00 to 570'000 corresponds to 20 kilometers.

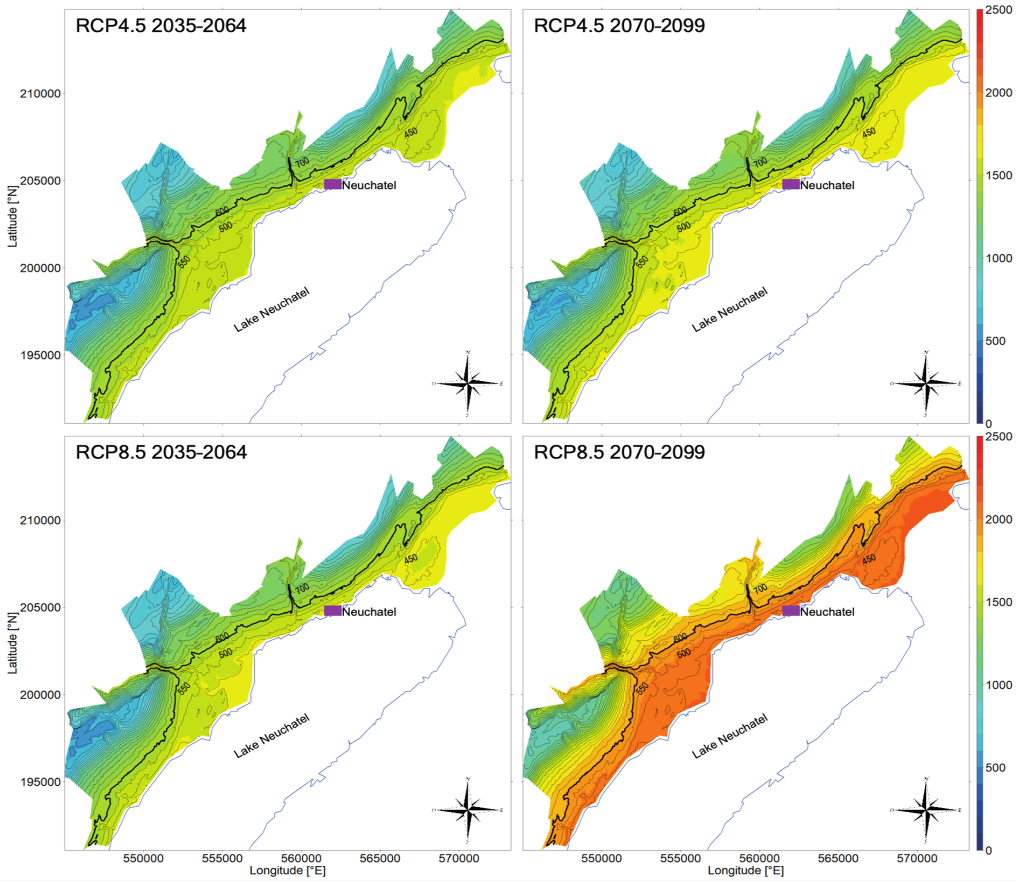


FIGURE 3. Trends in growing degree days (GDDs; base development temperature threshold [tb] = 10 °C) for the periods 2035–2064 and 2070–2099 with RCP4.5 and RCP8.5. The bold black line indicates the current elevational limit of the vineyards (600 m a.s.l.). Scale of the figure: 550'00 to 570'000 corresponds to 20 kilometers.

For the last decades (1991–2020), the mean start dates of first and second-generation European grapevine moths have been close to 2 May and 7 July, respectively (Table 2). No large changes were observed for the mean start date of European grapevine moth generations for future periods with either RCP4.5 or RCP8.5 (Table 2).

In the future, the mean date when a third generation could start will be close to 12 August with both scenarios RCP4.5 and RCP8.5 (Table 2).

3. Climatic acclimatisation of the American grapevine leafhopper in Neuchatel vineyards

The median number of eggs laid by an American grapevine leafhopper female per year has been, on average and median, approximately 26 eggs for the period 1991–2020 (Figure 4). The potential number of eggs per female is clearly expected to increase in the coming decades (Figure 4). For the future (mid and end of the century), our model predicts that the average and median number of eggs per female per year will be above 40, with both scenarios RCP4.5 and RCP8.5 (Figure 4). Interannual variability is expected to decrease slightly for both scenarios during the future, relative to the recent past (1991–2020). An estimated 95 % of the years will have more than 30 eggs per female per year with both scenarios RCP4.5 and RCP8.5 (Figure 4).

According to both scenarios, climatic conditions will be optimal for the American grapevine leafhopper by the middle, as well as by the end, of the 21st century.

The mean date of the first outbreak is expected to occur by the end of June under current climatic conditions (1991–2020). Our results show that this date will shift to the middle of June by the middle and by the end of the 21st century with both scenarios RCP4.5 and RCP8.5 (Table 3).

Frequency of third-generation outbreaks (50 % of flights)				
1991–2020	2035–2064		2070–2099	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
0 %	23 %	29 %	27 %	40 %

TABLE 1. Frequency of third-generation outbreaks of European grapevine moths in the different periods.

Mean date of generation start (10 % of flight) [DOY]					
Generation	1991–2020	2035–2064		2070–2099	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
G1	122	125	119	122	125
G2	188	185	180	182	179
G3	-	223	225	222	226

TABLE 2. Mean date of generation start for the European grapevine moth in the different periods.

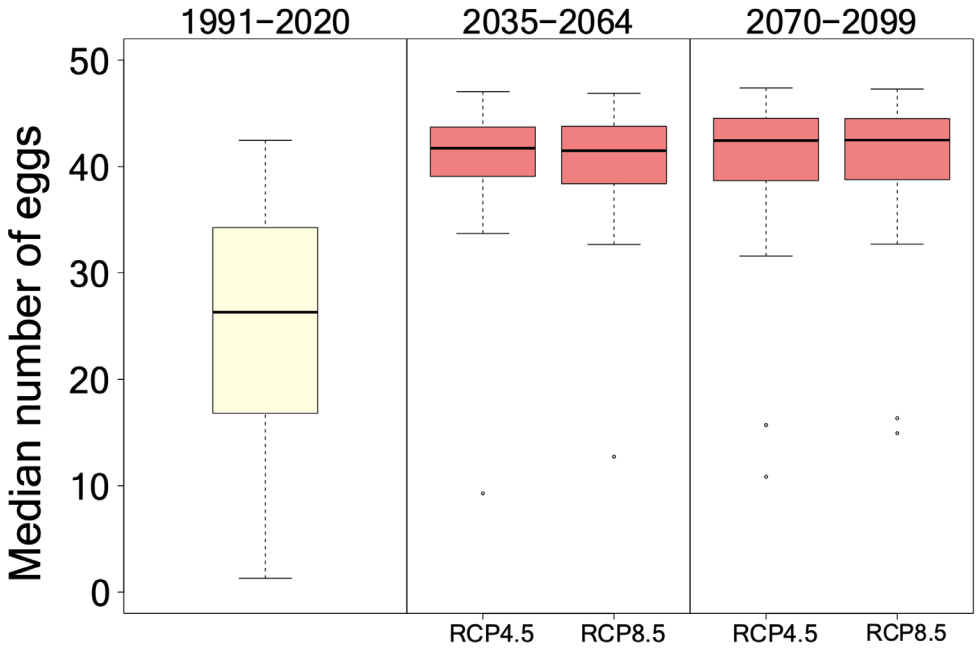


FIGURE 4. Median number of eggs per female and per year for three periods (1991–2020, 2035–2064, and 2070–2099) with RCP4.5 and RCP8.5 for future periods. Boxplot showing the minimum, the maximum, the sample median, and the first and third quartiles.

Interannual variability is predicted to decrease slightly with both scenarios during the first half of the 21st century and to increase again later (Table 3).

DISCUSSION

Our results show that GDDs increased significantly in Neuchatel over the last 5 decades, by approximately 425. By the middle of the 21st century, the mean number of GDDs during the development period is expected to exceed 1500 in both scenarios. This corresponds approximatively to the conditions found in Ticino (the southern side of the Alps) during the period 1980–2021 (Schneider *et al*., 2023). By the end of the century, the mean number of GDDs could reach 2000 GDDs in scenario RCP8.5, which is more than what we currently find anywhere in Switzerland. In scenario RCP4.5, GDDs would remain stable between the middle and end of the century, which corresponds to the current conditions in Ticino at lower elevations.

Mean date of first outbreak [DOY]				
1991–2020	2035–2064		2070–2099	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
179 SE = 8.06	165 SE = 7.21	165 SE = 7.10	161 SE = 8.78	161 SE = 8.70

TABLE 3. The mean date of the first outbreak by the American grapevine leafhopper. SE = standard error.

The increase in GDDs during the development season implies that polyvoltine species are likely to produce additional annual generations during the next decades. Our analysis concerning the European grapevine moth shows that a third generation can be expected to occur one year out of four by the middle of the century. The potential damage caused by this additional generation depends on other criteria than air temperature and photoperiod, such as the harvest period. An advanced grapevine phenology trend has been noted worldwide (*e.g.*, Jones and Davis, 2000; Ramos Martín *et al*., 2018). The harvest period is predicted to occur increasingly early in the year (Comte *et al*., 2022), it is likely that the third generation will break out after the harvest and therefore will not affect the grapes.

The values simulated by both scenarios for the coming decades show a slight decline compared with the values measured during the last decades, with the present values reached again around 2050. This might illustrate an underestimation of temperature forcing by the regional model. In this case, all our results should be interpreted with an offset of approximately 30 years. The next model generation should be available within a few years and should provide insight on this point.

While mean temperature during the development season has a major impact on voltinism, the population size of a species can be reduced by pest and natural control activities. European grapevine moths can be efficiently controlled using mating disruption (Ioriatti *et al*., 2011). This means that additional generations will not necessarily lead to more damage in the vineyards. An increase in CO_2 concentrations may impact the efficiency of mating disruption techniques for some pest species (Choi *et al*., 2018), but this process is not expected to have an impact on European grapevine moth control, according to Becker *et al*. (2023a). While mating disruption is currently used in the Neuchatel region, the European grapevine moth population can also be regulated using other methods such as egg parasitoids (Becker *et al*., 2023b; Benelli *et al*., 2023b). By contrast, the population of the American grapevine leafhopper is more difficult to control without using insecticides. It is currently controlled with natural pyrethrin (Linder *et al*., 2023). The spread of this pest in the region of Neuchatel would mean a major and increasing risk for the vineyards, as our results show that climatic conditions will become highly favourable for this species.

The number of American grapevine leafhopper eggs per female is highly dependent on air temperatures. Our results for this insect pest indicate that the climate over the coming decades will become highly favourable for this insect, with no significant difference between the two RCP scenarios (Figure 3 and Table 3), although the simulated mean annual GDDs for the period 2070–2099 are significantly higher with RCP8.5 than with RCP4.5 (Figure 2). This result can be explained at least in part by the fact that American grapevine leafhopper has a relatively wide range, and is well adapted to climate conditions which are quite diverse in terms of temperature (Chuche and Thiéry, 2014). The optimum air temperature for this insect's development (number of eggs per female) is 21–22 °C, and decreases progressively up to 30 °C. Air temperatures exceeding 30 °C have a negative impact on the number of eggs per female. The number of days with a maximum air temperature above 40 °C, which can be lethal for the insect, remains limited in the Neuchatel vineyard region with simulated data for the period 2070–2099, which suggests that the species will not be negatively impacted by the extreme hot air temperature. These results match those of Sneiders *et al*. (2019), where only the Ticino region in Switzerland is predicted to become slightly too warm for the American grapevine leafhopper by the end of the century with RCP8.5. If our simulation with RCP8.5 were extended to the 22nd century, it would probably show a decrease in American grapevine leafhopper eggs per female due to higher daily air temperature maxima.

Limitations of the study

Our study focused on mean temperatures during the development season, as they have a major influence on polyvoltine species. However, population dynamics are complex to model, and other climatic and non-climatic factors could be considered. In particular, minimum temperatures during winter have a major impact on the overwintering of pest species which are sensitive to cold events (Schneider *et al*., 2021). Extreme high temperatures are also likely to limit the spread of pest species, such as the European grapevine moth, during the development season (Iltis *et al*., 2018). Precipitation could also be considered, as it impacts specific species, such as the spotted wing drosophila [*Drosophila suzukii*] (Rossini *et al*., 2020). Moreover, the population size of a species is also driven by various non-climatic factors, such as pest control activities by humans, and predators and parasitoids, whose life cycle may also be affected by climate change. The tritrophic interactions of pest species may therefore be altered in the future, with potential impacts on the pests' immune systems (Thiéry *et al*., 2018).

Concerning the American grapevine leafhopper specifically, interactions between the vector and the phytoplasma have not been considered in this study but may be an important factor: it has been observed that the flavescence dorée's phytoplasma has a negative impact on the American grapevine leafhopper's fitness, especially on the females' progeny (Bressan *et al*., 2005). Climatic factors such as temperature might also have an effect, positive or not, on the phytoplasma itself, as is the case for *Candidatus (Phytoplasma) asteris*. The spread of this disease *via* the Cicadellidae *Macrosteles quadripunctulatus* is positively affected by higher temperatures (Maggi *et al*., 2014).

CONCLUSIONS

Our analyses show that the number of GDDs above temperature values offering favourable conditions to insect pest species (tb = 10 °C) has been increasing in Neuchatel over the last 50 years, by +85 GDDs per decade. By the middle of the 21st century, the number of GDDs is predicted

to continue to increase and reach conditions currently observed at lower elevations in Ticino, according to both scenarios RCP4.5 and RCP8.5. The number of GDDs is predicted to then remain relatively stable until the end of the century according to RCP4.5, while continuing to increase by +100 GDDs per decade according to RCP8.5.

These results suggest that polyvoltine species, such as the European grapevine moth, are likely to produce additional generations in the next decades compared with under the present conditions. The bioclimatic model we used confirms that temperature conditions would allow a third annual generation for the European grapevine moth one year out of four by the middle of the century, instead of the two generations observed until now. Furthermore, the increase in mean temperatures during the development season may favour species coming from warmer climates. Based on our bioclimatic model, temperatures during the development season will become more favourable for the American grapevine leafhopper in the next decades, according to both scenarios. These trends underline the importance of pest monitoring as a component of the adaptation strategies for the vineyards in the context of climate change.

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