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ORIGINAL RESEARCH ARTICLE

Characterisation of the vertical temperature gradient in the canopy reveals increased trunk height to be a potential adaptation to climate change

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ABSTRACT

Given the important role of temperature in vine development and grape composition, climate change has already impacted wine production. Adaptation strategies are needed in order to sustain the production of wines and maintain their typicity. Several levers of adaptation are possible, including the use of more heat and drought tolerant plant material, relocating the vineyard and adaptations in the cellar. The training system is also a potential lever for adaptation that is relatively easy to implement. Taking that avenue, a study of the vertical thermal gradient in the vine canopy was carried out in order to determine whether trunk height could be an adaptation strategy for manipulating micro-climate in the bunch zone. Temperature was measured at four different heights from the soil (30, 60, 90 and 120 cm) in two adjacent vineyard parcels. One parcel was managed with cover crop and the other by tilling the soil. The results of this study show that increased trunk height is not likely to significantly delay ripeness, but it could minimise the potential damages of both frost and heat wave events. Type of parcel management was found to have an effect: close to the ground, the cover crop parcel generally had lower minimum temperatures and higher maximum temperatures in comparison to the tilled parcel, exposing the vines to an increased risk of both frost and heat wave damage. When investigating the factors driving the vertical thermal gradient, soil moisture and weather type were found to have an impact. Some of these factors, like mean temperature and soil moisture, may exacerbate the vertical temperature gradient of maximum temperature in a climate change context and increase the risk of damages due to extreme temperatures.

KEYWORDS: Climate change, viticulture, grapevine, vertical temperature gradient, vineyard floor management, adaptation

INTRODUCTION

1. Impact of temperature on vine growth and grape berry composition

The grapevine is very sensitive to climate and in particular to temperature. Climate, which is a central component of terroir, plays a major role in the geographic distribution of vine-growing areas. Several agro-climatic indices, based on temperature summations over periods of time relevant to vine growth and development, have been created to characterise wine-production areas (Winkler, 1974; Huglin, 1986). Temperature has significant impact on the key phenological stages (i.e., budbreak, flowering and veraison), and therefore numerous predictive models based on temperature have been developed (Garcia de Cortazar Atauri *et al*., 2009; Parker *et al*., 2011; Chuine *et al*., 2013; Parker *et al*., 2020). There is an optimum temperature for vine development and grape ripening; extreme temperature events can cause damage to leaves and grapes. Negative temperatures (< -2.2 °C) after budburst can cause serious damage and reduce yield (Poling, 2008), while very high temperatures (> 35 °C) reduce anthocyanin concentration and alter photosynthesis (Kriedemann and Smart, 1971; Spayd *et al*., 2002). Temperature also affects grape berry composition, in particular the type and concentration of aromatic compounds (Mira de Orduña, 2010; Wu *et al*., 2019; Drappier *et al*., 2019; van Leeuwen *et al*., 2020).

2. Scale issues in climate analyses and factors influencing temperature distribution

Depending on the objectives of a given study and the accuracy of the data used, several scales can be used to characterise the climate: from macro scale (> 100 km) to describe wine regions to micro scale (< 1 km) to study climate or microclimate at parcel scale (Quénol *et al*., 2004; Neethling *et al*., 2019).

Overlaps exist between the different scales, and atmospheric conditions and weather patterns can impact climate at a very fine scale (Neethling *et al.*, 2019). Several studies have highlighted the large spatial variability that can be found at local scale (Bonnardot *et al*., 2012; Bonnefoy *et al.*, 2013; Madelin *et al*., 2014; Bois *et al*., 2018; de Rességuier *et al*., 2020). This variability is due to the interactions between atmosphere and weather types on the one hand, and local environment parameters like topography, vegetation type and canopy structure, water bodies and human-made infrastructures, on the other hand.

Vertical thermal profiles close to the ground are positively or negatively - depending on whether its night or day - impacted by weather type (overcast or clear), wind and soil moisture (Guyot, 2013; Monteith and Unsworth, 2013); for example, under clear skies, temperatures measured near the ground are lower than those measured by a reference weather station during the night and higher during the day.

At microscale (parcel level), other factors impact the temperature distribution, particularly the training system and canopy management practices. Planting density, vineyard layout and row orientations affect light interception and wind velocity and hence modify the microclimate inside a vineyard parcel (Reynolds and Vanden Heuvel, 2009; Hunter *et al*., 2020).

Under still wind conditions, the air temperature of the lower layers of the atmosphere is substantially influenced by the characteristics of the soil (e.g., albedo, texture and structure), which affect its conductivity and thermal capacity (Guyot, 1997). The restitution of heat by the soil during the night is a major component of the energy balance. Soil type and interactions with water dynamics also play a role. For example, frost is more likely to occur on a parcel with a sandy soil compared to a clay soil, because sand retains less humidity in the sub-surface layers; during the night, the associated lower thermal conductivity limits the release of the heat that had been stored during the day (Cellier, 1989).

Vineyard floor management can also impact the microclimate; for example, in frost conditions, plant cover can enhance cooling through evaporation at the beginning of the night and create a thermal insulating layer which limits heat rising from the ground (Trought *et al*., 1999).

3. Climate change impacts in the wine producing sector

3.1. Recent climate evolutions

The IPCC report provides many climate change trends based on a compilation of numerous global scientific studies (IPCC, 2021). Climate change is characterised by an increase of 1.09 °C in global surface temperature between the decade 2011-2020 and the preindustrial period 1850-1900, with large spatial variability at global scale. Greenhouse gas emissions have increased significantly over this period due to economic and human activities, thus impacting the climate system. The evolution of rainfall is more complex, with much more uncertainty and variability at any scale considered. Changes in extreme events have also been observed since 1950, with, for example, an increase in the frequency of heat waves in large parts of Europe (IPCC, 2021).

3.2. Observed effects on vine development and grape and wine composition

Global warming has already affected grapevine physiology, and earlier occurrences of phenological stages or harvest dates have been observed in many wine growing regions around the world (Jones *et al*., 2005; Petrie and Sadras, 2008; Tomasi *et al*., 2011; Bock *et al*., 2011; van Leeuwen *et al*., 2019). Grape composition has been modified, with higher levels of sugar and a lower concentrations of anthocyanins and organic acids in grapes (Mira de Orduña, 2010; Pieri *et al.*, 2016; Wu *et al*., 2019; Drappier *et al.*, 2019). Modifications to wine aromas have also been observed. In the particularly warm 2003 vintage in Bordeaux, cooked and dried fruit flavours were more intense compared to other vintages from the same decade (Pons *et al*., 2017). A link between higher temperatures and a decrease in aroma precursors of the thiol family in grapes has also been found (Wu *et al*., 2019).

3.3. Future evolution and impacts on the wine sector

Surface temperature is projected to rise during the 21st century at a magnitude that will depend on human GHG emissions, and heat waves are predicted to occur more often and last longer (IPCC, 2021). This temperature increase is not expected to be homogeneous; there will likely be specific regional trends (IPCC, 2021). As a consequence of temperature increase, an advance in the subsequent phenological stages is predicted, which is in line with recent observations (Duchêne *et al*., 2010; Xu *et al*., 2012; Cuccia *et al*., 2014; Fraga *et al*., 2016). This earliness of the vine's annual cycle will likely lead to the advancement of the grape ripening period, which will take place earlier in the season and in warmer temperature conditions; this may in turn affect grape composition and balance, and therefore the typicity of the produced wines. Early budburst could lead to more frequent spring frost damage, but projections vary depending on the model used and the geographical location (White *et al*., 2006; Poling, 2008; Sgubin *et al*., 2018; Molitor and Junk, 2019).

3.4. A challenge for the wine industry: how to adapt to climate change

Even if climate change is not spatially uniform, and will therefore probably not affect wine growing areas in the same way, adaptation is expected to be essential to maintaining wine quality and typicity. Several levers that limit the effect of increased temperatures have been identified (van Leeuwen *et al*., 2019). Plant material adapted to warmer temperatures can be selected; i.e., late ripening varieties and clones, or rootstocks which induce a longer cycle in the associated variety (Duchêne, 2016). Another possible avenue for adaptation would be to better adapt plant material to local climate variability or to relocate vineyards to a higher latitude or an increased elevation (Bonnardot *et al*., 2012; Fraga *et al*., 2012; Jones and Alves, 2012; Bonnefoy *et al*., 2013; Hannah *et al*., 2013). Certain viticultural techniques can be applied to adapt to global warming; for example, changing planting density or leaf area to fruit weight ratio, or promoting late pruning to delay bud break (van Leeuwen *et al.,* 2019; Gutiérrez-Gamboa *et al.,* 2021; Naulleau *et al.,* 2021). Techniques for adaptation in the cellar include alcohol reduction or acidification, or the selection of yeasts which produce less alcohol for a given concentration of sugar (Dequin *et al*., 2017).

In this context, a study of the vertical temperature gradient in the vine canopy was carried out to determine whether increasing the trunk height could be an adaptive solution for limiting the impact of climate change on vine development and grape composition. For this purpose, the temperature was recorded at four different heights between 0.3 and 1.2 m in two vineyards and with two different floor management techniques (cover crop and tillage) in the Bordeaux area from 2016 to 2020.

MATERIALS AND METHODS

1. Experimental set-up

The experiment for measuring the vertical temperature gradient was conducted in a dry-farmed vineyard located in the Bordeaux area in the Saint-Émilion PDO area (France).

Two adjacent vineyard parcels were selected for this study in a flat area at an elevation of 36m. The parcels were located on sandy-clay soil and had both been planted with *Vitis vinifera* L. cv. Merlot in 1972 at a density of 6,000 vines per hectare. The vines were simple Guyot-pruned and vertical shoot-positioned (VSP trellis). The first supporting wire was located 45 cm above the ground, corresponding to the bunch height. The trimming height was 1.6 m. The rows were

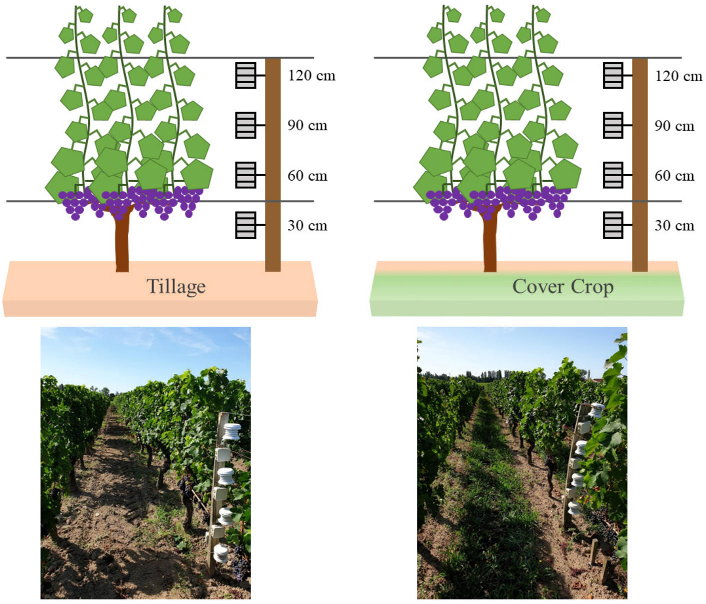

FIGURE 1. Diagram of the study device (top) and picture of the experimental design taken on 16 August 2019 (bottom).

planted in a north-west/south-east direction and vine spacing was 1.4 m (inter-row) by 1.2 m (inter-vine). One parcel was managed with a sown cover crop (CoCr), while in the other the soil was tilled (Till) (Figure1). The soil was mechanically tilled under the row in both parcels, and the width of inter-row grass strip was 0.9 m for the CoCr treatment.

2. Temperature measurement

Three replicates of four temperature data loggers Tinytag Talk2-TK-4023 (Gemini Data Loggers, UK) were set up on vine posts in the two adjacent vineyard parcels at different heights above the ground: 30 cm, 60 cm, 90 cm and 120 cm (Figure 1). The replicates were located in the same rows or in adjacent rows with a maximum distance of 20 m. The two parcels were approximately 20 m apart. The thermistor probes (PB-5005-0M6, Gemini Data Loggers, UK) were installed inside solar radiation shields (Type RS3). From 2016 to 2020, the data loggers recorded both minimum (Tn) and maximum (Tx) hourly temperatures. The time system used was UTC. The daily minimum temperature was defined as the extreme hourly minimum temperature between the previous day at 6pm and the day at 6pm, and the daily maximum temperature corresponded to the extreme hourly maximum temperature between the day at 6am and the next day at 6am. The average daily temperature was computed as $(Tn + Tx)/2$.

A quality assessment of the recorded minimum and maximum temperatures was carried out through a graphical analysis by plotting the daily data obtained from all the sensors. Outliers and deviations were visually detected and eliminated from the database (4.9 % of the total records). The different replicates at the same height and treatment were also compared for a more accurate detection of deviations. Missing or outlier data were replaced by the average temperature of the sensors located at the same height and treatment.

Daily data from the weather station of Saint-Émilion (Météo-France), located 100 m from the study parcels, was used to assess the synoptic climate conditions and, indirectly, surface soil wetness in order to explain any observed differences in vertical temperature gradient. The daily data used were the minimum and maximum temperatures measured at a height of 1.7 m, the duration of insolation, rainfall and wind speed at a height of 10 m.

3. Temperature indices

To quantify temperature differences between the sensors by treatment and height, the Canopy Winkler degree day summation was used and calculated according to de Rességuier *et al*. (2020). This index is based on the sum of mean temperatures in the canopy above 10 °C from 1 April to 31 October (Winkler, 1974). Other climate indicators calculated in this paper were the average daily minimum and maximum temperatures over the growing season from 1 April to 30 September. The diurnal temperature range during the ripening period (DTR) was also calculated. DTR corresponds to the mean daily range between the maximum day temperature and the minimum night temperature from August to September (Ramos *et al*., 2008; Neethling *et al*.,2012; Shaw, 2017). This indicator is linked to wine quality, with higher DTR supposedly resulting in better red wines (Ramos *et al*, 2008).

The GSR model was used to determine the impact of temperature on the timing of sugar ripeness (Parker *et al.*, 2020). This model is based on the sum of daily mean temperatures above 0 °C cumulated from the 91th day of the year (DOY). The sugar content is determined when the thermal sum reaches a threshold value specific to each grapevine variety. The threshold value for *Vitis vinifera* L. cv. Merlot reaching 220 g/L of sugar in grape berries is 2,962 degree-days.

In this study, we also used the temperature differences relative to the temperatures recorded at 30 cm (i.e., 120 – 30 cm; 90 – 30 cm; 60 – 30 cm) in order to neutralise the daily temperature variations and to quantify the temperature gradients between heights.

Climatic variables which can have an impact on the relative temperature gradients were selected according to Cantat (Cantat *et al*., 2012). Data for the statistics on the temperature gradients and these climatic variables was collected from the Saint-Émilion weather station. The selected variables were average temperature, sunlight ratio and wind speed at a height of 10 m, all at a daily time step. The daily sunlight ratio corresponds to the ratio measured daily insolation duration (> $120 W/m^2$) to the day length.

4. Soil moisture

Soil moisture was estimated by using a soil water balance model according to Lebon *et al*. (2003) and retained as a potential driver for the thermal gradient. The parameters used in the model were: row orientation in terms of degrees from the North in a clockwise direction (-25 ° for CoCr treatment and -10 ° for Till treatment), latitude (44,92 °), inter-row vine spacing (1.4 m), minimum foliage porosity (10 % for CoCr treatment and 25 % for Till treatment), soil albedo (0.18), soil water holding capacity (200 mm), proportion of the inter-row surface covered by the cover crop for CoCr treatment (64 %), foliage height (1.15 m) and foliage width (0.45 m).

The original soil water balance model was adapted to the presence of cover crop on part of the soil surface by allocating a specific water reserve to the grass on the corresponding proportion of soil surface. This water storage capacity was assumed to be completely independent of the main water reserve; this means that the vine roots did not take up water from this soil volume, and that the grass roots did not take up water from the main volume explored by the vine roots. Grass transpiration was calculated by the model according to the same principles, including regulation by water depletion. The grass global stomatal conductance, and therefore grass transpiration, responded to the fraction of transpirable soil water (FTSW) of the cover-crop soil volume in a similar way, as did vine conductance and transpiration. The cover-crop separate water holding capacity parameter was set at 30 mm in all simulations.

The climate input variables used for running the Lebon *et al.* model were collected from the Saint-Émilion weather station: daily rainfall (mm), daily minimum and maximum temperature (°C), daily solar radiation (MJ.m^{-2}) and reference evapotranspiration ET$_0$ (mm) from Penman-Monteith equation.

5. Statistical analysis

The average daily minimum and maximum temperatures over the growing season, Canopy Winkler Index and DTR per treatment and height (years 2016 to 2020) were represented in boxplot graphs (R software). Daily relative temperatures at heights of between 120 and 30 cm per soil management treatment, and the daily minimum and maximum temperature differences at the height of 30 cm between CoCr and Till, were represented in a monthly time step (years 2016 to 2020) in boxplot graphs. In the boxplots the outliers are represented by dots. These correspond to values higher than the value of the 3rd quartile plus 1.5 times the interquartile interval, or less than the value of the first quartile minus 1.5 times the interquartile range.

The effects of height and vineyard floor management on the minimum and maximum average daily temperatures during the growing season, the Canopy Winkler index and DTR were analysed using a linear mixed-model (Pinheiro *et al.*, 2021). Height and vineyard floor management were considered as fixed effects and year as a random effect to account for the repeated measurements (Pinheiro and Bates, 2000). When a significant effect of the interaction between height and vineyard floor management was found, height was analysed separately for each soil management treatment. When a significant effect of height on minimum and maximum average daily temperatures during the growing season, the Canopy Winkler index and DTR was found, multiple comparisons were conducted to test differences between heights using Tukey's HSD test.

To assess the effects of climatic variables and soil moisture on vertical temperature gradients for minimum and maximum temperatures, two linear mixed models were used, with sunlight ratio, mean temperature, wind speed and simulated soil moisture considered as fixed effects and the year as a random effect. Residuals of all linear mixed models were checked in order to fulfill the assumptions of normality. The models were fitted using the "lme" function in the nlme package (Pinheiro *et al.*, 2021) in R.4.1.0 (R Development Core Team, 2021).

RESULTS

1. Vertical temperature gradient according to vineyard soil management

The analysis of daily temperatures over the growing season revealed the significant effects of height and treatment (Figure 2 (A) and (B) and Table 1). The temperature gradient analysis showed that height had an effect on daily maximum temperature over the growing season. Conversely, minimum temperature was not affected by height for the tillage treatment (Figure 2A and B). A reverse gradient was observed between minimum and maximum temperature over the growing season: near the ground the minimum temperature was lower (except for in the tillage parcel where this effect was not significant) and the maximum temperature higher. Despite the significant effect of height, the gradient was very low for minimum temperature (particularly in the tillage parcel) and greater for maximum temperature. The gradient between the minimum and maximum temperature during the growing season was greater at a height of 30 cm than at 120 cm. The air temperature in the cover crop was lower in terms of minimum temperature and higher for maximum temperature, compared to the tilled parcel. Relative temperature differences between heights were lower for minimum temperature and greater for maximum temperature (Table 2).

The Canopy Winkler Index was calculated for each sensor from 2016 to 2020, and significant effects of height and soil management were found (Figure 2C, Table 1). Regardless of soil management, the highest temperature sums were recorded close to the ground and the tilled parcel was warmer than the cover crop parcel. Even if the differences between heights were significant, there were only 69 degree-days between 120 cm and 30 cm (Tilled and Cover crop parcels averaged, Table 2). Assuming that grapes are located at these heights, the potential impact on maturity as calculated using the GSR model was found to be limited, with a difference of three days to reach 220 g/L of sugar content for Merlot at a height of 120 cm compared to 30 cm for the cover crop treatment, and a difference of 2 days for the tilled treatment (Table 2).

An effect of vineyard floor management on the diurnal temperature range (DTR) was found, with DTR being greater for the cover crop parcel (Figure 2D, Table 1). A significant height effect was also observed, with greater DTR at 30 cm compared to 120 cm (Table 2). This effect was not significant when comparing 30 and 60 cm, and it was more pronounced in the cover crop parcel compared to the tillage parcel (Figure 2).

2. Relative daily temperature gradients and impacting factors

2.1 Relative daily temperature gradients between 120 and 30 cm

A strong vertical gradient for minimum temperature was measured from November to May with cooler temperatures close to the ground most of the time (Figure 3A). The seasonal dynamics of both treatments were similar, but the cover crop parcel showed larger vertical gradients compared to the tilled parcel. The gradient was particularly high in April, especially in the cover crop parcel, with gradients of up to 2.7 °C during the sensitive period just after budburst when spring frost events can harm young shoots. In contrast, a very small and reverse gradient was observed between June and October (minimum temperatures slightly warmer close to the ground).

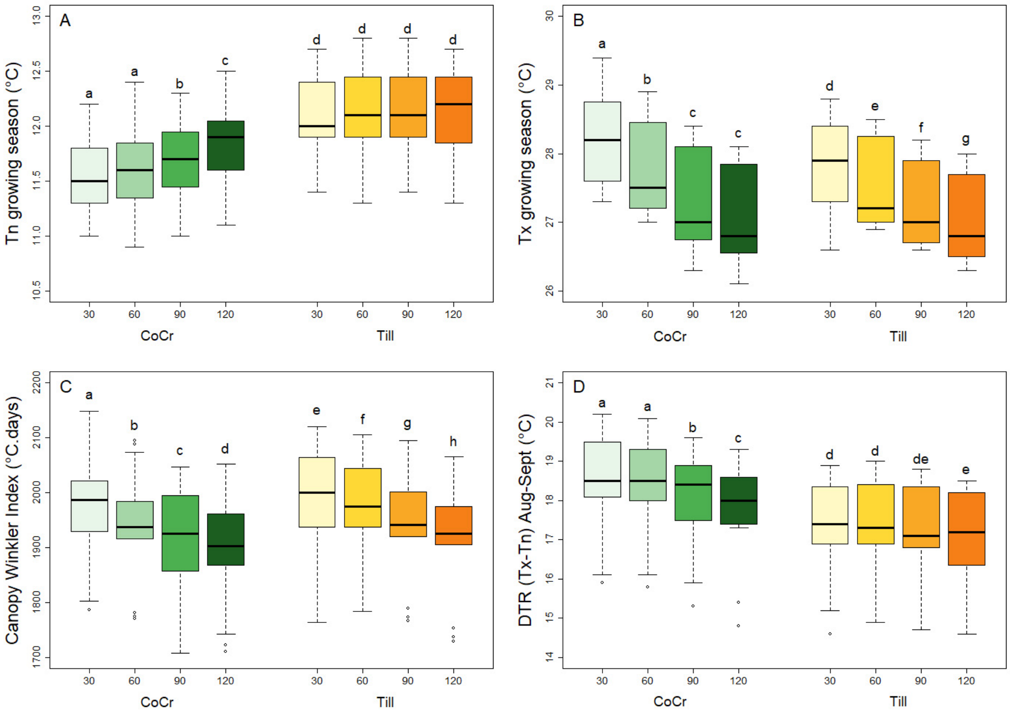

FIGURE 2. Effect of vineyard floor management (Cover crop = CoCr and Tillage = Till) on A) daily minimum, B) maximum temperature over the growing season (from 1 April to 30 September), C) the Canopy Winkler index, and D) the diurnal temperature range during ripening period (2016 to 2020). Values on the x-axes refer to the sensor height from the ground (cm). Analyses were carried out separately for each soil management treatment. Different letters above bars indicate significant differences between heights (at P < 0.05).

TABLE 1. Linear Mixed-Models output on the effect of vineyard floor management and height on the climate indicators (Tn and Tx during the growing season, Canopy Winkler Index and DTR (°C) over five years (2016 to 2020). The effect of height was analysed separately for each soil management treatment when the interaction height*soil was significant.

	Canopy Winkler Index (°C.days)			Tn growing season (°C)			Tx growing season (°C)			DTR (Tx-Tn) Aug-Sept (°C)		
	Chisq	Df	Pr (> Chisq)	Chisq	Df	Pr (> Chisq)	Chisq	Df	Pr (> Chisq)	Chisq	Df	Pr (> Chisq)
Height (cm)	176.6	3	< 0.001	42.0	3	< 0.001	323.1	3	< 0.001	84.8	3	< 0.001
Treatment	34.8	1	< 0.001	697.2	1	< 0.001	28.1	1	< 0.001	306.5	1	< 0.001
Height*Treatment	4.9	3	0.180	32.7	3	< 0.001	10.8	3	0,010	11.9	3	0.008
CoCr Height (cm)				69.8	3	< 0.001	203.0	3	< 0.001	73.8	3	< 0.001
Till Height (cm)				4.2	3	0.2	128.2	3	< 0.001	19.9	3	< 0.001

For maximum temperature, the gradient was substantial from April to September (growing season), with higher maximum temperatures close to the ground, despite some rare days of thermal inversion (Figure 3B). This gradient sometimes reached up to 2.7 °C, which is comparable to the greatest minimum temperature gradient. For maximum temperature, there was an effect of soil management as well, with repeatedly higher gradients between 120 cm and 30 cm in the cover crop treatment.

2.2. Factors impacting the relative daily temperature gradient between 120 cm and 30 cm

Taking the previously described results into account (Figure 3), the analysis of the factors impacting temperature gradients was carried out for the periods with the greatest gradients. A statistical analysis was performed on data from November to June for minimum temperature, and on data from April to September for maximum temperature.

Regardless of the season and the gradient, simulated soil moisture had the strongest effect on the vertical temperature gradient between 120 and 30 cm in all linear mixed models: the drier the soil, the greater the gradient of minimum and maximum temperatures (Table 3).

The effect of the sunlight ratio was also significant, with a larger gradient during clear sky conditions. This effect is more pronounced in the cover crop treatment than the tilled treatment (Table 3).

TABLE 2. Relative temperatures calculated for the temperature indicators (Tn and Tx during the growing season, Canopy Winkler Index and the DTR (°C) over five years (2016 to 2020).

Temperature indicator	Relative temperature (cm)	CoCr	Std dev	Till	Std dev
Tn Growing Season (°C)	120 cm - 30 cm	0.3	± 0.1	0.0	± 0.1
	90 cm - 30 cm	0.1	± 0.1	0.1	± 0.1
	60 cm - 30 cm	0.0	± 0.1	0.0	± 0.1
Tx Growing Season (°C)	120 cm - 30 cm	-1.1	± 0.3	-0.8	± 0.4
	90 cm - 30 cm	-0.9	± 0.4	-0.6	± 0.4
	60 cm - 30 cm	-0.4	± 0.2	-0.2	± 0.4
Canopy Winkler Index (°C.days)	120 cm - 30 cm	-73	± 31.1	-65	± 40.5
	90 cm - 30 cm	-67	± 45.2	-42	± 40.7
	60 cm - 30 cm	-32	± 19.9	-18	± 45.6
DTR (Tx-Tn) (°C)	120 cm - 30 cm	-0.8	± 0.4	-0.4	± 0.5
	90 cm - 30 cm	-0.5	± 0.5	-0.2	± 0.4
	60 cm - 30 cm	-0.1	± 0.4	-0.0	± 0.4
Date of 220 g/L of sugar concentration	120 cm - 30 cm	2.8	± 1.2	2.4	± 1.4
	90 cm - 30 cm	2.6	± 1.5	1.7	± 1.4
	60 cm - 30 cm	1.3	± 0.9	0.7	± 1.3

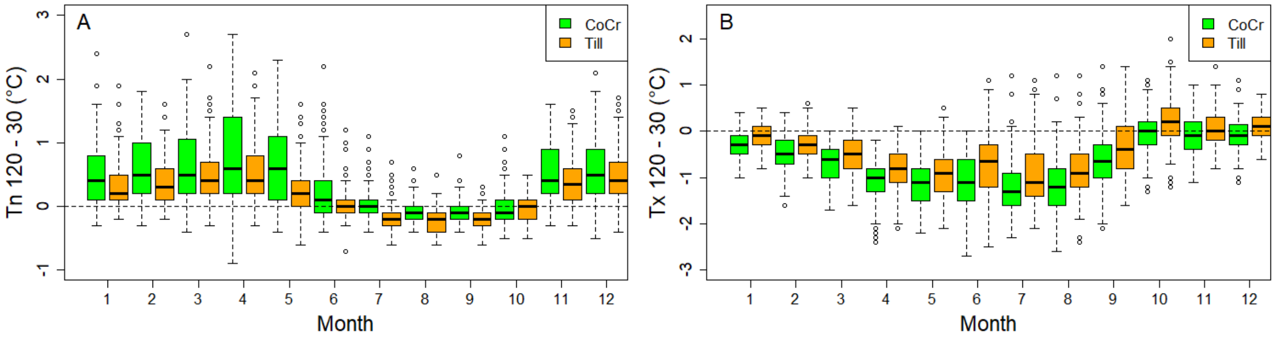

FIGURE 3. Seasonal and treatment effect (CoCr = Cover crop and Till = Tillage) on daily relative (120 cm – 30 cm) A) minimum and B) maximum temperatures (2016 to 2020).

The vertical gradient of maximum temperature during the summer was accentuated by an increase in mean temperature. From November to June, however, the vertical minimum temperature gradient increased with lower mean temperatures (Table 3).

Except for the minimum temperature gradient in the cover crop parcel, which was non-significant, wind accentuated the gradients (Table 3).

3. Impact of soil management on temperature close to the ground

The comparison of the temperatures in both vineyard floor management treatments at 30 cm highlighted a soil management effect close to the bunch zone. In the cover crop parcel, the minimum temperatures (monthly averages) were found to be generally lower and the maximum temperatures generally higher than those in the tillage parcel (Figure 4). The differences reached 2.2 °C at most, with an average of 0.3 °C for the maximum temperature and 0.4 °C for the minimum temperature. The differences were greatest in the summer.

4. Extreme temperature analysis

4.1. Hourly temperature analyses of two extreme days

The analysis of the night of frost on 27 April 2017 revealed that independently of the treatment, minimum temperatures near the ground were coldest (Figure 5A). Compared to the tilled parcel, the cover crop parcel showed a greater vertical gradient (1.7 °C compared to 0.9 °C) and lower temperatures (by 0.5 °C) in the fruit zone (height of 45 cm).

During the heat wave of 23 July 2019, regardless of vineyard soil management, the warmest maximum temperatures in the afternoon occurred close to the ground (Figure 5 B). For this specific day, an effect of soil treatment was observed, the tilled parcel being 0.8 °C cooler than the cover crop parcel in the bunch zone.

4.2. Study of all extreme temperature days

To determine the possible generic characteristics of the previously shown results, an analysis of all days with Tn < -2.5 °C at 30 cm and all days with Tx> 35 °C at 30 cm was carried out from 2016 to 2020.

TABLE 3. Statistical results of linear mixed models explaining vertical temperature gradients (120 cm - 30 cm) for CoCr and Till treatments as a function of climatic variables and simulated soil moisture, calculated from daily data from 2016 to 2020 (ns: not significant, * significant at 0.05, ** significant at 0.01, *** significant at 0.001).

	Gradient Tn 120 cm - 30 cm (CoCr) November-June					Gradient Tx 120 cm - 30 cm (CoCr) April-September				
	Slope	Std. Error	t-value	Significance	Interpretation	Slope	Std. Error	t-value	Significance	Interpretation
Sunlight ratio (%)	0.0978	0.0163	5.9924	***	Gr Tn ↗ when SR ↗	-0.1234	0.0179	-6.8917	***	Gr Tx ↗ when SR ↗
Mean temperature (°C)	-0.1384	0.0152	-9.0931	***	Gr Tn ↗ when Tm ↘	-0.0532	0.0173	-3.0713	**	Gr Tx ↗ when Tm ↗
Wind speed at 10m (m/s)	-0.0075	0.0157	-0.4804	ns	ns	-0.0485	0.0168	-2.8828	**	Gr Tx ↗ when Wind ↗
Simulated soil moisture (%)	-0.1448	0.0162	-9.1332	***	Gr Tn ↗ when Sm ↘	0.238	0.0172	13.8457	***	Gr Tx ↗ when Sm ↘
	Gradient Tn 120 cm - 30 cm (Till) November-June					Gradient Tx 120 cm - 30 cm (Till) April-September				
	Slope	Std. Error	t-value	Significance	Interpretation	Slope	Std. Error	t-value	Significance	Interpretation
Sunlight ratio (%)	0.0372	0.0136	2.7286	**	Gr Tn ↗ when SR ↗	-0.0512	0.0201	-2.5504	*	Gr Tx ↗ when SR ↗
Mean temperature (°C)	-0.0379	0.0124	-3.0518	**	Gr Tn ↗ when Tm ↘	-0.0386	0.0182	-2.1243	*	Gr Tx ↗ when Tm ↗
Wind speed at 10m (m/s)	0.0435	0.0127	3.4168	***	Gr Tn ↗ when Wind ↗	-0.1175	0.0176	-6.6687	***	Gr Tx ↗ when Wind ↗
Simulated soil moisture (%)	-0.0736	0.0138	-5.3356	***	Gr Tn ↗ when Sm ↘	0.2632	0.0199	13.2369	***	Gr Tx ↗ when Sm ↘

Sr = Sunlight ratio; Tm = Mean temperature; Wind = Wind speed at 10 m; Sm = Simulated soil moisture; Gr = Gradient.

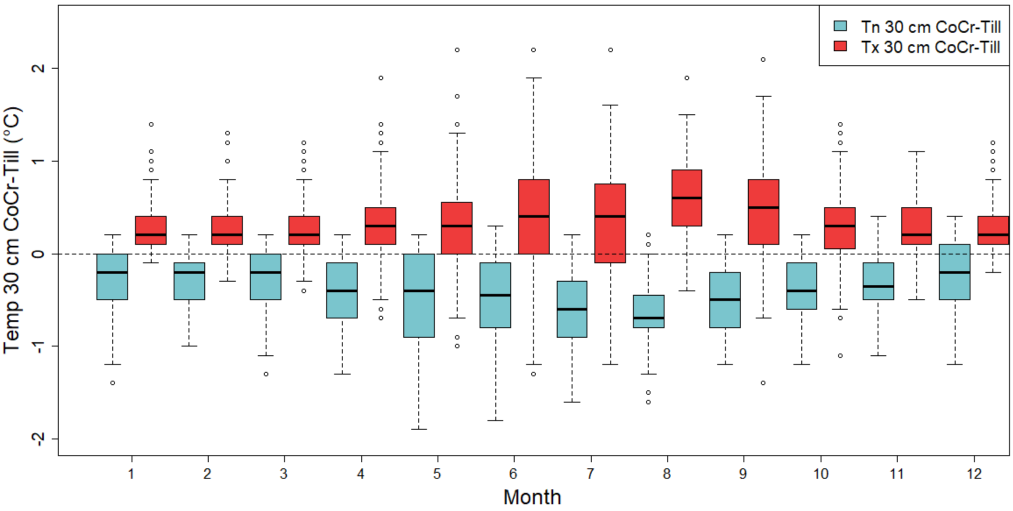

FIGURE 4. Daily minimum and maximum temperature differences at 30 cm between cover crop and tillage treatment for each month in the period 2016-2020.

Sixty-seven days at Tn< -2.5 °C were recorded in the cover crop parcel compared to 50 in the tilled parcel. During these frost risk nights, the minimum temperature was almost always colder in the cover crop parcel (66 days/67). Regarding maximum temperatures, 56 days at Tx> 35 °C were recorded in the cover crop parcel versus 47 in the tilled parcel. For 45 of these 56 days, Tx at a height of 30 cm was warmer in the cover crop parcel.

There was therefore a greater risk of frost and exposure of the bunches to higher temperatures in the cover crop parcel.

4.3. Tampering extreme temperatures by increasing trunk height

To determine whether increasing trunk height could be a means of adapting to climate change by limiting the effects of extreme temperatures in the bunch zone, the corresponding differences between measurement heights were calculated from the extreme temperature data extracted previously (Table 4).

As illustrated in Table 4, increasing trunk height could help to reduce air temperature in the cluster zone during days of extreme heat and raise the temperature during frosty nights.

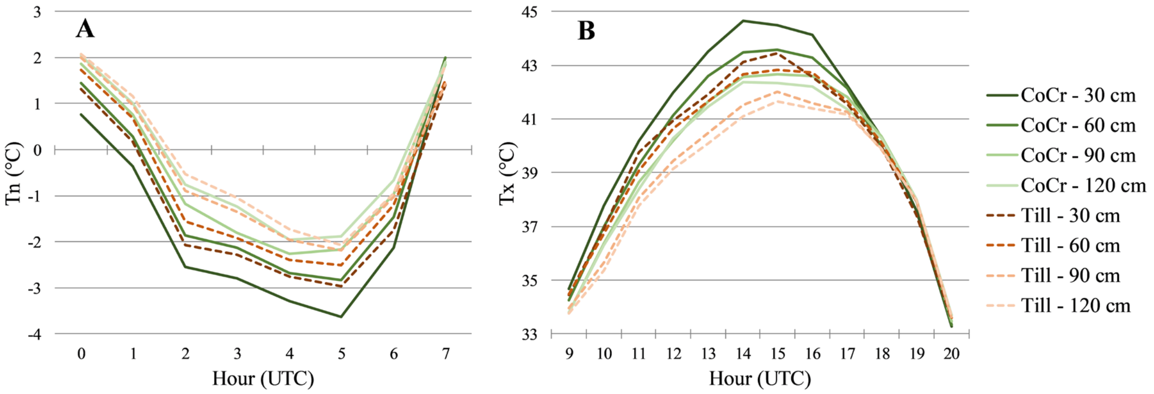

FIGURE 5. Hourly temperature distribution against height and soil management treatment during the spring night of frost on 27 April 2017 (Tn, A) and the heat wave of 23 July 2019 (Tx, B).

These changes are more pronounced in the cover crop parcel, which, as seen before, is more exposed to extreme temperatures. On tilled soils, an increase in trunk height may not greatly limit the risk of frost damage, but it may help to reduce the impact of excessively high temperatures.

DISCUSSION

1. Effect of distance from the ground on temperatures and grape and wine composition

The temperature profile pattern results are largely in agreement with classical profile studies carried out near the ground, either over bare soil or near canopies, with lower night time temperatures and higher noon or afternoon temperatures observed at lower heights or at maximum leaf area density height (Oke, 1970; Winkel *et al*., 2009; Monteith and Unsworth, 2013). The effects of ground surface roughness or the vertical profile of the leaf area density were not considered here since the grapevine canopies were identical; the effect of air-flow stability was considered only through the observation of variations with wind speed.

This study shows that even if there was a significant effect of height (distance from the ground) on temperatures and bioclimatic indices, the differences were not substantial enough to potentially delay reaching maturity by more than a few days through increasing trunk height. Increasing trunk height could, however, potentially increase the minimum temperature in the bud and cluster zone and hence limit the risk of frost damage during the sensitive period after budbreak. Another possible advantage of trunk elongation is the decrease in maximum daily temperature during the growing season and in maximum temperature within the fruit zone during extremely warm days (Tx> 35 °C). Given that high temperature during the ripening period negatively impacts wine aromatic profiles, it is important to avoid or reduce extremely high temperatures in the cluster zone as a way of adapting to climate change. Several studies have shown the impact of high temperatures on wine aromatic profiles; for example by increasing the compounds involved in dried fruit aromas (Pons *et al*., 2017) or decreasing the rotundone or methoxypyrazine concentration in grapes and wines (Falcão *et al*., 2007; Harner *et al*., 2019) and aroma precursors of the thiol family (Wu *et al*., 2019). High temperatures also reduce anthocyanin concentrations in grapes, which is detrimental to red wine quality (Spayd *et al*., 2002). The reduction in the herbaceous aromas of late ripening grapevine varieties, such as Cabernet-Sauvignon, is a positive effect of high temperatures; however, with the evolution of the climate towards increasingly higher temperatures, the negative impacts are expected to overrule potential positive impacts and change the typicity of the wines produced. Therefore, increasing trunk height could be an important adaptive means of reducing high temperatures in the cluster zone and limiting these negative effects.

The diurnal temperature range during the ripening period was greater at 30 cm than at 120 cm. According to the literature, this indicates that wines produced from vines with higher trunks will be of lower quality (Ramos *et al*., 2008). However, close to the ground not only DTR is greater, but so are maximum temperatures. As specified by several authors, higher daytime maximum temperatures during the ripening period are not always desirable and can lead to vine stress and impaired aroma profiles in wines (Ramos *et al*., 2008; Shaw, 2017). There is probably a threshold above which the increase of maximum temperature during the ripening period will have a negative impact on wine quality. Hence, the positive effects of lower maximum temperatures at a greater distance from the ground may outweigh the negative effects of smaller DTR. This is particularly likely in a climate change context in which an increase in the frequency of heat waves is expected.

Given the influence of the training system on the vertical gradient of temperature (Reynolds and Vanden Heuvel, 2009; Hunter *et al*., 2020), an increase in trunk height can lead to a modification of the microclimate by impacting, for example, air flow patterns, which could also alter vertical

TABLE 4. Average differences of Tn and Tx across different heights and effect of soil management treatment during extreme temperature days (Tn< -2.5 °C (n=67) and Tx> 35 °C (n = 56) at 30 cm recorded on CoCr treatment from 2016 to 2020). Numbers after "±" sign are standard deviation.

	Tn < -2.5 °C at 30 cm on CoCr treatment			Tx > 35 °C at 30 cm on CoCr treatment		
	CoCr	Till	Average (CoCr and Till)	CoCr	Till	Average (CoCr and Till)
60 cm - 30 cm	0.3 ±0.2	0.1 ±0.1	0.2 ±0.2	-0.7 ±0.3	-0.5 ±0.4	-0.6 ±0.3
90 cm - 30 cm	0.5 ±0.3	0.2 ±0.2	0.4 ±0.3	-1.3 ±0.5	-0.9 ±0.5	-1.1 ±0.4
120 cm - 30 cm	0.8 ±0.4	0.3 ±0.3	0.5 ±0.3	-1.6 ±0.5	-1.3 ±0.5	-1.4 ±0.4

temperature profiles. Hence, the results presented here apply to VSP trellised vines planted at a density of 6,000 vines per hectare and give a valuable indication of the usefulness of increasing trunk height, under the assumption that air temperature profiles are not disturbed too much. However, any potential disturbance would likely be lower off-season, in the absence of leaves, and therefore also during periods of frost risk. The next step would be to compare the vertical gradients in plots with contrasting trunk heights, to confirm the results of this study and provide a direct proof of the positive effects of higher trunks in terms of limiting extreme maximum and minimum temperatures in a context of climate change.

2. Soil management effect

The study parcels were located in a wine producing estate and soil maintenance was not specifically carried out for this research project. Soil management operations were carried out several times a year in the inter-row and under the row. It is possible that at some periods of the year, depending on the climatic conditions of the vintage, some grass was present in the tilled parcel. During the summer, the grass was parched in the cover crop parcel during the dry periods; however, this would also likely happen if the trunk height were increased as an adaptation to climate change.

This study shows that there is an effect of soil management on the vertical temperature gradients. Differences in daily minimum and maximum temperatures between heights of 120 and 30 cm were clearly larger in the cover crop parcel compared to the tilled parcel. However, the effect of vineyard floor management on the bioclimatic indices was small due to compensation between minimum and maximum temperatures.

At 30 cm above the ground, minimum air temperature was lower for the cover crop compared to tilled soil, and similar results were found in the frost-risk day analysis. The observed phenomenon is probably due to an insulating action of the grass, which limits the release of heat from the soil during the night. This effect could be due to the fact that air movement within the grass cover is limited, hence convection fluxes are reduced and heat transfer is then almost exclusively molecular (Monteith, 1957; Oke, 1970). Other effects, such as soil compaction, cannot be excluded, but they were not investigated in this study (Cellier, 1991; Slater and Ruxton, 1954). Therefore, increased trunk height, in association with tillage, could be an adaptive solution to limit the risk of spring frost damage. The results presented here are specific to the experimental set up. Other studies have shown the influence of ground cover or soil thermal conductivity on surface temperature during nights of radiative frost. For example, disking or tilling the soil just prior to a frost period creates an insulating layer between the soil and the air, reducing the soil's ability to release heat during the night and increasing the risk of frost damage (Cellier, 1989).

Regarding maximum air temperature, a soil management effect was also highlighted in the present study. Close to the ground (30 cm), warmer temperatures were recorded in the cover crop plot compared to the tilled plot and the same trend was observed during most of the extreme warm days (> 35 °C). These results seem to contradict previous studies where maximum temperatures were reduced by the cooling effect of the grass transpiration (Pradel and Pieri, 2000). Here, the non-monitored grass cover may have dried out at certain stages in certain years, which could have triggered a mulch effect. Other possible explanations include differences in albedo or soil moisture, which may have an impact on the surface temperature and on the heating of the air above the ground. These hypotheses, however, need further investigation to be confirmed. In the conditions of this study, tilling the soil could reduce the impact of extreme maximum temperatures during the grape ripening period.

3. Climatic variables driving the vertical temperature gradient

The statistical analysis of factors impacting the vertical temperature gradient showed the importance of weather types, as well as the impact of soil moisture. These results were in line with the scientific literature, with the exception of wind, which surprisingly increased the gradients in ours models; this was probably due to the impact of the vertical wind profile within the row: the air may have been strongly mixed near the top of the row, due to increased turbulence, while the air near the ground may have remained still and become warmer (Riou *et al*., 1987). In the view of these results, the current climate evolution is expected to amplify temperature gradients. Indeed, climate change projections agree on an increase in air temperature, and assuming maintained rainfall patterns or reduced rainfall depending on the area, these conditions are likely to reduce soil moisture, which may increase vertical temperature gradients. The increase in mean temperature that is expected with climate change could also accentuate the gradient of maximum temperature during the summer. In the light of these observations, increasing trunk height can be considered a potential adaptive solution to climate change.

In view of the results of the extreme temperature analysis, it could be useful for wine-growing estates to increase trunk height; for instance, from an original height of 45 cm to one of 90 cm. The consequences would be a reduction in maximum temperatures during heat waves by 0.8 °C on average, and an increase in minimum temperatures during nights of frost by 0.4 °C (Table 4). The potential reduction in canopy height could be compensated for by increasing the trimming height by 40 cm (e.g., from 160 cm to 200 cm) without changing farm equipment or the leaf area-to-fruit weight ratio. A reduction in the leaf area-to-fruit weight ratio may also further limit the impact of climate change on grape composition by decreasing sugar content without increasing total acidity (Parker *et al*., 2014).

CONCLUSION

This study investigated the vertical temperature gradient inside the vine canopy and the factors driving this gradient in the context of climate change. Increasing trunk height has a limited effect on the modelled timing of berry ripeness; it could, however, significantly reduce the negative impacts of both spring frost and summer heat waves. This study also highlights factors driving the vertical temperature gradient, such as soil management and moisture, and weather type. Furthermore, it has increased the knowledge and understanding of microclimate at vineyard plot scale. The results are expected to assist winegrowers in their adaptation strategies to climate change, particularly in terms of soil and canopy management.

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