# The impact of climate change on the income of wine producers in the Bordeaux region


## Abstract

In the Bordeaux region, climate change is characterised by an increase in average temperature and a decrease in rainfall. These changes are having a very significant impact on wine producers, which are seeing an increase in vineyard area, but a decrease in yield and income. We use very precise individual, structural and financial data at farm level (FADN database), which we combine with weather data to measure the impact of climate change on vineyards. Estimates from structural econometric models highlight the important role of rainfall in reducing yields during the growing season, particularly from May to July. Temperatures play a more complex role depending on the stage of development of the vines. We show that farmers respond to these phenomena by combining different strategies: increasing vineyard area, prioritising operational expenditure over long-term investment strategies, and using adaptive risk management techniques such as crop insurance, irrigation and retail selling. These results suggest that wine growers are effectively adapting to climate change and its adverse effects on yield and income volatility.



**Keywords:** Climate change, Adaptation strategy, Income, Wine production

## 1. Introduction

There is a growing awareness, both in academic research and in the policy agenda, that climate change has and will have a strong impact on the agri-food sector (Falco et al., 2019; Lamonaca et al., 2021; Santeramo et al., 2021). Within the agri-food sector, wine grapes (*vitis vinifera*) and the wine industry are particularly affected by climate change, with potential impacts on yield, quality and ultimately economic viability (Jones et al., 2005; Holland and Smit, 2010). Evidence of this phenomenon is provided by an empirical literature (Ashenfelter and Storchmann, 2016; De Salvo et al., 2015).

At the level of the Bordeaux region, according to Hannah et al. (2013), a decline in wine production of 85% is possible by 2050. Furthermore, vines are perennial and the climate is expected to change significantly during their expected productive life of more than fifty years. Accordingly, the potential impact on vines currently being planted represents an immediate risk -or opportunity- for wine companies (Webb et al., 2008; Hewer and Gough, 2020). For this reason, the links between climate change and the wine industry deserve to be studied.

Empirical studies on the impact of climate change on wine production use two different approaches. The first one is based on the consequences of future climate change scenarios on wine business characteristics, which makes it more suitable for measuring climate risk exposure due to the uncertainty of climate change scenarios and transition processes (De Salvo et al. 2015; Sacchelli et al., 2017; Hewer and Gough, 2020; Lamonaca et al., 2021).

The second approach focuses on the relationship between historical weather conditions and wine business characteristics (Holland and Smit, 2014; Jones, 2012; Shaw, 2017). It assumes that a better understanding of the structural relationships between climate variables and wine business variables helps to predict the impact of future climate change on wine business. In addition, this approach makes it possible to observe the adaptation strategies already implemented to face the observed climate evolution during the last decades.

Following the second approach, the objective of this paper is to measure the impact of the evolution of weather conditions over the last three decades on the gross revenue of Bordeaux wine producers. Risks associated with climate change are usually divided into physical risk (*i.e.,* how the business is and will be affected by climate change) and transition risk (*i.e.,* how the business must adapt to a more sustainable business model) (Bank of England, 2015). In this paper, we explore both the impact of physical risk on the Bordeaux wine industry and the adaptation strategies implemented by wine producers.

In order to propose an explanatory model, we also examine the impact of past weather conditions on two important determinants of wine producers' gross revenue: vineyard area and yields. This decomposition into area and yields is traditionally used to study the response of farms to shocks (Haile et al., 2016; Kim and Moschini, 2018). We also investigate the potential mitigating effect of different adaptation strategies.

The paper makes several contributions. By examining the impact of weather variables on the income of wineries and incorporating financial characteristics at the farm level, the paper goes beyond previous studies that mainly focus on the impact of climate change on wine quantity (yield) and quality. Rather than describing technical adaptation methods in vineyards, the paper examines more strategic and managerial aspects, such as the level of investment and insurance, the evolution of land use, the marketing strategy and the reduction of pesticide use.

The main findings are that rainfall is the most detrimental to wine yields, in line with previous studies (Lamonaca et al. 2021). Temperature increases have opposite effects depending on the season: a significant negative effect on yields when they occur during the bloom period (May to July in the northern hemisphere), and a positive effect when they occur during the ripening period (August). In the case of the Bordeaux region, the global effect of temperatures is not significant in our study. The study also clearly shows that adaptation strategies play an important role in mitigating the negative effects of weather variability.

The paper is structured as follows. Section 2 presents the impact of climate change on the main dimensions of the wine business model and the possible adaptation strategies. Section 3 presents the data, variables and empirical model. Section 4 develops the results of the empirical study and finally section 5 offers some conclusions and perspectives.

## 2. Literature review

This section examines the impact of weather conditions on wine business characteristics and the adaptation strategies implemented by wine growers.

### 2.1. The impact of climate change on wine producers

Physical climate risk refers to the direct losses caused by climate events that companies may face. Physical risks are typically decomposed into two main dimensions: chronic risk (*i.e.,* the incremental evolution of climate variables) and the risks associated with extreme weather events. This decomposition is well illustrated by the IPCC's (2014) definition of impacts: "The term impacts is used primarily to refer to the effects of extreme weather and climate events and climate change on natural and human systems" (page 124). Research has already explored the impact of chronic and extreme event dimensions on various aspects of the wine business and industry. The primary impacts of climate change are potential losses in product quantity and quality. Additional risks are related to the impact on revenues and production costs throughout the supply chain (Mozell and Thach, 2014).

Several theoretical and empirical studies using different approaches have shown that climate affects vineyard yields (Adams et al., 2003; Lobell et al., 2006; Fraga et al., 2014; De Salvo, et al. 2015; Lamonaca et al., 2021). The effect of the different weather parameters on yield (temperature, rainfall, extreme events) can have a different sign depending on the period in which they occur, the particular characteristics of the world region (New versus Old World), the country, the terroir and each individual farm (Webb et al., 2007). Merloni et al. (2018) report that higher temperatures can have a negative impact on grapevine yield and quality. An increase in extreme high temperatures in summer can have a negative impact on grapevine phenology (Briche et al., 2014). Ramos et al. (2008) suggest that the seasonal distribution of rainfall is important, with higher rainfall levels being critical for grapevines at the beginning of the growing season (*i.e.,* spring), while more stable rainfall is desirable from flowering to ripening (*i.e.,* summer and autumn). The recent empirical study by Lamonaca et al. (2021), based on a multi-country sample, shows that the higher the average summer temperatures in producing countries, the lower the grape yield. Higher rainfall is beneficial for yield during the early growing season (*i.e.,* spring), but detrimental during the late growing season and harvest time *(i.e.,* summer and autumn).

Previous studies have also considered the impact of climate change on winemakers' profitability in terms of gross revenue (De Salvo, et al. 2015), net revenue or profit (Haeger and Storchmann, 2006; Ashenfelter and Storchmann, 2010a; Ashenfelter and Storchmann, 2010b; Marinoni et al., 2012). Climate change affects the quantity and quality of wine, which in turn affects the market price and the volume of sales. Climate change also disturbs the costs incurred in the production process, with implications for total costs. In terms of revenue, the increase in temperature compared to climate normality has a different impact on gross revenue depending on the location of the vineyard, the grape variety and the vinification process and period. A positive relationship between temperature and revenue was found by De Salvo et al. (2015) for Romanian wine and Antoy et al. (2010) for the European Union. A negative relationship was also found between gross revenue and total rainfall during the growing period (Salvo, et al., 2015; Bär et al., 2015). An increase in rainfall during the growing season has a negative impact on grape production and quality due to increased problems with pests and pathogens. In particular, the resulting increase in air and soil humidity favours the spread of downy mildew, which reduces vineyard revenues (Fraga et al., 2012).

### 2.2. Adaptation strategies of wine producers

The impact of climate change on wine producers depends to a large extent on their adaptation strategy. Responses to climate change in the wine industry consist of two strategies: mitigation and adaptation (Galbreath, 2011, 2014).

Mitigation strategies refer to changes that reduce the company's impact on climate change (*e.g.* reducing carbon emissions or absorbing these emissions by creating sinks). We consider two mitigating strategies: reducing pesticide use and selling through short supply chains. The first strategy has an impact on carbon emissions of the growers' suppliers and also contributes to the sustainability of agricultural practices. The second reduces the carbon emissions of the retail process. The projective study of Sacchelli et al. (2017) highlights that organic farming is a fundamental strategy in all the scenarios they studied.

Adaptation-based strategies seek to change products and processes in response to direct threats from climate change. We include information on the presence of irrigated land as a process adaptation technique. Several empirical studies include irrigation as an adaptive-based technique (Kurukulasuriya et al., 2011; De Salvo, et al. 2015; Lamonaca et al. 2021). In order to proxy the adaptive capacity of each individual farm, we select two variables: the experience of the winemaker (proxy is age) and his/her general and agricultural education level. In fact, the adaptive capacity of farms depends on the knowledge of management options for adaptation, which could be approximated by the educational level of the farmer.

By altering the efficiency of production factors and the profitability of wine crops relative to other crops, climate change can affect land allocation. If the effects of climate change are not too severe, farmers will try to compensate for the decline in yields by increasing the area under cultivation. But if the impact is such that profitability becomes too low, farmers will switch to other land uses. The ability to switch from wine to another agricultural product or even to other activities is a fundamental adaptation strategy. According to Lamonaca et al. (2021), it is consistent with the choices of a representative farmer maximising expected profit. They find that higher annual temperatures in the producing countries are beneficial for vineyard area. This is true for both Old and New World producers, although the effect is much larger for Old World producers. On the other hand, heavy rainfall is significantly associated with lower vineyard area. They find that the negative effects of higher annual rainfall are entirely associated with New World producers, whereas Old World producers do not seem to be affected by changes in rainfall levels.

As the source of the dynamics of production factors, investment is an important vector of adaptation. Investment can support the strategy of moving vineyards to northern regions, as already observed in Europe or California (Kenny and Harrison, 1992; Fraga et al., 2013; Ashenfelter and Storchmann, 2016). Winegrowers can plant new cultivars that are better adapted to the future climate (Schultz and Jones, 2010; Fraga et al., 2012; Ruml et al., 2012). Cultivar substitution is a very expensive activity from an economic and organisational point of view. According to Sacchelli et al. (2017), this adaptation strategy could only be implemented for high-value wines (at least 20 €/l). Using an optimisation approach and an empirical application in the Chianti region in Italy, Zhu et al. (2016) show that the combination of vineyard relocation and the adoption of drought-resistant grape varieties is the best solution from a financial efficiency point of view. Winegrowers can also invest in irrigation methods in the vineyard or cooling systems in the winemaking process. Finally, investments allow for the diffusion of technological progress, which is certain to occur in the face of climate change (Galbreath and Oczkowski, 2016). Investments can also be intangible. De Salvo et al. (2015)

or Dutz et al. (2014) show the importance of investing in knowledge, in the training of winegrowers and especially in the awareness of farms and winegrowers about the effects of climate change.

Finally crop insurance policies are an indirect form of adaptation strategies (Sacchelli et al., 2017). Current insurance characteristics derive from national legislation. The main parameters that affect the purchase of insurance contracts are: the premium (the annual fee due from a farmer to a multi-risk insurance to cover all damages from extreme events); a deductible representing the threshold of damage (computed on yield) that has to be crossed to pay indemnity (*i.e.,* a deductible is the initial share of the damage that is not protected) and the percentage of a premium covered by public funding. All these parameters may deteriorate in the future due to the increase frequency of extreme events.

In order to assess the effect of climate change on wine producers, we propose the model presented in Figure 1. From this structural model, we deduce simultaneous equations models that link climate change to yield and vineyard surface and finally to the gross revenue of wine farms.

***Figure 1. Impact of weather and climate change on farm's area, yield and revenue***

### 3. Method and data

As with more general risk management models, the impact of climate change on wine businesses can be broken down into three interrelated building blocks: characteristics of the business model that can be affected by climate change (Y), climate change risk factors (CC), and adaptation strategies that can mitigate the impact of climate change on the companies' business model (AS). For Y, our models focus on three fundamental aspects: yields, gross revenue and vineyard area. The climate change risk factors (CC) are divided into three categories: climate variables (long-term, evolution over 30 years), weather variables (short-term, annual/monthly) and extreme events. Adaptation strategies include insurance policies, adaptation of the production and marketing process (no pesticides, irrigation, short food supply chains), changes in production factors (vineyard area, investments and human capital, education level). Due to a lack of information, we do not examine the adaptive role of specific technical solutions such as anti-hail nets, fans, heating/candles.

In this section we present, on the one hand, the individual farm (Y and AS) and weather (CC) data and, on the other hand, the estimated econometric models. Note that the vineyard area variable is included in the Y and AS categories, and that yields are affected by climate change (Y) but are also important determinants of farm income. This observation leads us to choose a simultaneous equations model.

### 3.1. Data

We combine data on the characteristics of the Bordeaux wine industry at farm level with weather and climate indicators collected at the Bordeaux-Mérignac airport weather station. The farm level data come from the French Farm Accountancy Data Network (FADN) database for the years 2000 to 2020. This database contains a set of accounting, individual and structural information on a sample of French farms representative of production and regions. More specifically, we select wineries which are located in the Bordeaux region and whose main production is AOC quality wine (99% of them). Due to the annual rotation of the sample, between 175 and 195 farms are included annually. Table 1 shows the variables used in the analysis.

***Table 1. List of variables included in the analysis at farm level***

Weather data come from the weather station at the Bordeaux-Mérignac airport, which is the main weather station for the Bordeaux region. These data have been used for numerous studies in the region (Jones et al., 2005; Lecocq and Visser, 2006; Tonietto and Carbonneau, 2004, Baciocco et al., 2014). Although more stations could be useful, Lecocq and Visser (2006) showed that the variation in weather over the Bordeaux region is small enough that more detailed data from multiple stations or for each specific vineyard would not significantly improve the robustness of the analysis. In addition to the annual indicators (average temperature and cumulated rainfall), we include the occurrence of unfavourable events during the growth phase of the vines, such as hail and frost. We also account for climate change over recent decades by comparing the evolution of key indicators such as average temperature, rainfall and frost with a 30-year rolling average. Such deviations account for climate change in line with the literature (Sachelli et al., 2017; Lamonaca et al., 2021). Table 2 shows the weather data used in the analysis and how it was calculated.

*Table 2. List of weather variables considered in the analysis*

### 3.2. Econometric models

The empirical strategy is based on a 'Ricardian approach' (Mendelsohn et al., 1994), which is one of the most widely used micro-econometric methods for assessing the long-term impacts of climate change on agriculture. Our aim is to estimate the impact of global climate change on local farms. Weather indicators are measured both on an annual basis and on a relative basis (change compared to previous decades).

Our contribution to the literature is to consider the influence of weather and climate on farms in a systemic way because of their interdependence. To this end, we choose to analyse the impact of physical risk on wine yield, vineyard area and gross revenue of individual farms. For chronic risk, we consider the evolution of temperature, rainfall and frost. For extreme weather events, we have selected hail, heat and frost events, firstly during the most important period for viticulture (1 April-31 October), and secondly for more detailed stages using monthly indicators for the periods of budbreak (March-April), bloom (May-June), veraison (August-September) and ripening (September).

As a result of the sample rotation, the panel is unbalanced and we take year effects into account.

$$\begin{cases} Yield_{it} = \alpha_1 + \alpha_2 Weather_{it} + \alpha_3 Farmer_{it} + \alpha_4 Workforce_{it} + \alpha_5 Acreage_{it} + \\ \alpha_6 Irrigation_{it} + \alpha_7 Investment_{it} + \alpha_8 FE_{1i} + \alpha_9 YE_{1t} + \varepsilon_{it} \qquad (1) \\ \\ VineyardArea_{it} = \beta_1 + \beta_2 ClimateChange_{it} + \beta_3 Workforce_{it} + \beta_4 Investment_{it} + \\ \beta_5 FE_{2i} + \beta_6 YE_{2t} + \mu_{it} \qquad (2) \\ \\ Revenue_{it} = \gamma_1 + \gamma_2 Production_{it} + \gamma_3 Acreage_{it} + \gamma_4 Insurance_{it} + \gamma_5 Retail_{it} + \\ \gamma_6 NoPesticides_{it} + \gamma_7 OpEx_{it} + \gamma_8 FE_{3i} + \gamma_9 YE_{3t} + \nu_{it} \qquad (3) \end{cases}$$

Where: *Yield* is the quantity of wine produced per hectare, *VineyardArea* is the cultivated vineyard area in hectares, *Revenue* is the gross wine production in euro per hectare, *Weather* includes the average temperature, rainfall and sunshine as well as the occurrence of hail and frost, *ClimateChange* is the deviation of some weather parameters (average temperature and rainfall, and frost days) from their rolling average over the last 30 years, *Farmer* refers to the farm holder's age and education, *Workforce* corresponds to the available work units on the farm, *Irrigation* is the share of irrigated cultivated area on the farm, *Investment* is net investment (*i.e.,* gross investment minus depreciation), *OpEx* are operating expenses, *Insurance* is the purchase of a crop insurance policy against weather hazards, *Retail* corresponds to the adoption of retail selling for all of part of the production, *NoPesticides* denotes the use of no chemical inputs during the production, *FE* are fixed effects, *YE* are year effects, $\varepsilon$, $\mu$ and $\nu$ are the error terms, assumed to be *iid*. *i* and *t* are the farm and the time period respectively.

Several techniques can be used to estimate simultaneous equations. We opt for three-stage least squares (3SLS), which takes into account the potential correlation between error terms across equations. This method seems to be the most appropriate for correctly identified equation systems (Biørn, 2016). For the analysis, we consider a fixed effects model to account for the unobserved farm effects as non-random variables.

The models are estimated twice to account for the phenological stages of Bordeaux vines (Baciocco et al., 2014; Jones and Davis, 2000). The first estimation considers the growing season (1 April-31 October), taking into account weather indicators calculated during this period. The second estimation considers more detailed stages using monthly indicators of temperature, rainfall and frost: budbreak (March–April), bloom (May–June), veraison (August–September) and ripening (September). This four-season model follows the climate literature (Kurukulasuriya et al., 2011; Massetti et al., 2016) and assumes that seasonal differences in temperature and rainfall are likely to affect vine productivity.

## 4. Results

We first present statistics on the weather and climate of the Bordeaux region, highlighting the main trends over the last 50 years. We then present the results of the econometric models and discuss their implications.

### 4.1 Descriptive statistics

First of all, there has been a progressive and regular increase in temperatures since 1970, with an average increase from 16.5°C to 19°C (Figure 2). This change has a direct impact on all the indicators used in the literature to approximate the effect of temperature on agricultural and viticultural yields.

***Figure 2. Evolution of average temperature and other related indicators at Bordeaux-Mérignac weather station from 1970 to 2020***

The correlation between these indicators is shown in Table 3. From a methodological point of view, it tends to indicate that temperatures and their evolution alone are sufficient to measure the impact of global warming on wine yields. Only the minimum temperature does not correlate with the other indicators.

***Table 3. Correlation of temperature indexes at Bordeaux-Mérignac weather station from 1970 to 2020***

We also take into account other key meteorological parameters, such as rainfall and two types of climatic events that have a strong impact on vineyards. There has been a slight decrease in rainfall over the last 50 years, but this phenomenon is neither uniform nor continuous. Dry and wet years seem to alternate in longer cycles in the years 2000 and 2010 than in the years 1970 to 1990. In addition to this effect, climate change is also reflected in a very marked decrease in the number of days with hail and frost, which have almost disappeared since 2014 (with the notable exceptions of 2019 and 2022).

***Figure 3. Average rainfall and days of frost and hail at Bordeaux-Mérignac weather station from 1970 to 2020***

In the literature, the effect of climate change is calculated using deviations from the mean. We choose to use 30-year rolling averages, in line with Lemonaca et al. (2021), to obtain a better fit. The bars in Figure 4 show the steady increase in average temperatures and an irregular but clear decrease in precipitation and frost.

***Figure 4. Rolling deviations of temperature, rainfall and frost at Bordeaux-Mérignac weather station from 2000 to 2020***

The last 20 years have seen significant changes in wine production (Figure 5). Firstly, the average vineyard area has increased, especially in the early 2010s, from an average of 23 to 29 hectares (+19.48% over the period). Symmetrically, wine yields have fallen sharply (-31.96% over the period). Due to a kind of "compensatory effect", total wine production fell by only 9.44% over the period.

***Figure 5. Vineyard area, wine yield and wine revenue in the Bordeaux region from 2000 to 2020***

There was also a sharp fall of 20.28% in revenue from wine (in euro per hectare), but this should not overshadow the 31.26% increase in revenue from wine (in euro per hectolitre) (Table 4). Bordeaux wine producers have therefore tried to focus on quality rather than quantity. However, they have faced difficulties in recent years, with a dramatic year in 2020 characterised by an EBITDA well below the average and losses for most farms. Operating costs have also risen steadily over the past 20 years, to the detriment of investment, perhaps reflecting a search for short-term adjustments.

At an individual level, Bordeaux's winegrowers are becoming increasingly well educated, with a significant increase in the proportion of graduates from agricultural universities. The average age is also increasing. At a structural level, farms are becoming less labour-intensive, which is reflected in increased mechanisation and the search for productivity gains, even as the area under cultivation increases.

As regards risk management, winegrowers have several tools at their disposal: firstly, irrigation, which concerns over 8% of farms in 2020. Secondly, they insure their crops to a very high degree (78% in 2020, more than twice the national average for winegrowers), which allows them to protect the value of their production against weather risks. While 75% of them use retail selling and short food supply chains, few farms manage without pesticides, reflecting the vulnerability of vines and the need to protect them with phytosanitary products.

***Table 4. Summary statistics of wine-producing farms in the Bordeaux region in 2000, 2010 and 2020***

### 4.2 Econometric models

The results of the econometric models consider aggregated weather and climate indicators measured in a first step over the whole growing season (Table 5) and then in a second step measured on a monthly basis (Table 6).

***Table 5. Results of the simultaneous equation modelling for years 2000-2020, seasonal indicators***

***Table 6. Results of the simultaneous equation modelling for years 2000-2020, monthly indicators***

At the aggregate scale the weather parameter that most influences *Wine yields* is rainfall (Table 4). Rainfall plays a very important role in the development of vine buds but increased rainfall can reduce the quality of the grape and favour the development of vine diseases. Similarly, high temperatures or sunshine, as well as the occurrence of frost or hail, are detrimental to the development of the vines. However, the impact of these different factors is not significant in our overall model

For this reason, we examine their effect on a monthly basis, which is more precise and allows us to focus on the different stages of vine growth. The results are then more precise and easier to interpret (Table 5). In particular, we can see that the effect of temperature is strongly nuanced according to the month. High temperatures between May and July (bloom) are very detrimental to the yield of the vine, while warmer temperatures in August and September (veraison and ripening) are more beneficial. Similarly, excessive rainfall between May and June (bloom) and in September (ripening) is detrimental to the plant. Finally, a late frost (May) causes a very sharp drop in yield, whereas a frost in April has no significant effect when the plant is at a less advanced stage of development.

Age and education of the farmer have a positive effect on yield, reflecting the importance of background and experience. Irrigation also increases yields by protecting the crop. However, net investment has no effect, while labour-intensive farming reduces productivity.

Due to the nature of vines, *Vineyard area* is influenced by long-term dynamics, the first of which is climate. The results (Tables 4 and 5) clearly show that farmers are adapting to climate change, with differences depending on the factors considered. As a result, the increase in temperature leads to a reduction in the area cultivated. However, the effect is balanced: the early heat of the May-June flowering period encourages a reduction in the area cultivated, while the summer heat of August (veraison) has the opposite effect.

At the aggregate level, the evolution of rainfall does not show a marked effect on the evolution of the cultivated area. However, it appears that an increase (or decrease) in rainfall between June and August leads to a reduction (or increase) in vineyard area. Combined with the previous results, it seems that winegrowers compensate for the loss of wine yield due to lower rainfall by increasing vineyard area. We also note that increased investment allows growers to increase their vineyard area. Conversely, a labour-intensive operation leads to smaller areas, presumably with the aim of quality production.

Finally, we consider the parameters affecting *Wine revenue*. Not surprisingly, the wine income of the farm is positively influenced by its wine yield. Similarly, a small vineyard area reduces the farm's income. It is interesting to note the positive effect of several risk management techniques: firstly, the purchase of crop insurance, which protects the yield of farmers affected by weather hazards; secondly, retailing, which increases the outlets and selling prices of farmers; thirdly, the absence of phytosanitary products, which is associated with quality production and is therefore more highly valued. Operating costs also contribute to increased income by enabling the farm to be managed more efficiently.

## 5. Conclusion

In the Bordeaux region, climate change is characterised by an increase in average temperature and a decrease in rainfall, while, paradoxically, certain risks such as frost and hail are decreasing. These major changes over the last 50 years have had a significant impact on the volume and value of wine production since the beginning of the millennium. The major climatic changes described above have had a very significant impact on vineyards: While their area is increasing, their yields and resulting income are decreasing.

Thanks to precise data at farm level and detailed measurements of weather and climate, we have been able to highlight their effects on yields and incomes, as well as on cultivated areas, using simultaneous equation models. In particular, we underline the important role of rainfall in reducing yields during the growing season, especially from May to July. Temperatures play a more complex role depending on the stage of development of the vines.

Faced with these phenomena, wine producers are responding on several levels at once. First, they are increasing their vineyard area to compensate for declining yields. Second, they are prioritising short-term operating expenses over long-term investment strategies to gain agility. Third, they are using adaptive risk management techniques, some of which are widespread (crop insurance and retail selling), while others are less common (irrigation and pesticide-free production).

These results suggest that wine growers are adapting to climate change, even though it is challenging the financial sustainability of their businesses. In this context, their increased level of education and experience is an advantage. An appropriate policy of increasing knowledge on how to respond appropriately to climate change could have an even more significant moderating effect on the relationship between climate change and the economic conditions of Bordeaux wine producers.

Some aspects of current adaptation strategies also raise concerns for the medium to long term future. They can be used in the face of still moderate climate change, such as that observed in recent decades, but their ability to cope with more severe changes is questionable. This raises questions about the future development of risk management tools. For example, irrigation may help to cope with more frequent and longer heat waves and water supply restrictions. However, all climate change scenarios predict an increasing insurance gap (the difference between the desired level of insurance protection and the level of insurance that is achievable and affordable), raising questions about the future availability of crop insurance policies if the frequency of extreme events increases significantly. A pesticide-free strategy may eventually be called into question in view of the increase in old diseases and the emergence of new ones (Caffarra et al. 2012). In addition, some of the adaptation techniques (irrigation, OGM, pesticides) have potentially dangerous environmental consequences.

Adaptation strategies are likely to require more integrated structural and costly changes in a more transdisciplinary framework in the future (Snyder et al., 2011). Future research should focus on this issue and on identifying the most effective technical, human and financial strategies for adapting to climate change.

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**Table 1. List of variables included in the analysis at farm level**

| | Variable | Definition | Unit |
|---|---|---|---|
| **Wine production** | **Vineyard area** | Total area devoted to wine-growing | ha |
| | **Wine production** | Wine production | hl |
| | **Wine yield** | Wine yield | hl/ha |
| | **Wine revenue** | Value of the wine production | €, €/ha, €/hl |
| **Individual variables** | **Age** | Farmer holder's age | Years |
| | **General education** | Farmer's level of general education | Dummy (1 if higher education) |
| | **Agricultural education** | Farmer's level of agricultural education | Dummy (1 if higher education) |
| | **Workforce** | Total workforce | Annual working units (AWU, AWU/ha) |
| **Financial variables** | **Turnover** | Value of the production | € |
| | **EBITDA** | Value of the "earnings before interest, taxes, depreciation, and amortization" | € |
| | **Net income** | Value of the net income | € |
| | **Net investment** | Gross investment - Amortization | € |
| | **Operating expenses** | Value of the operating expenses | € |
| | **ROA** | Value of the "return on assets" | % |
| **Adaptation strategies** | **Crop insurance** | Purchase of a crop insurance policy | Dummy (1 if Yes) |
| | **Irrigation** | Irrigated area | Dummy (1 if Yes) |
| | **No pesticides** | No pesticide expenditures | Dummy (1 if Yes) |
| | **Retail selling** | Sales through short food supply chains | Dummy (1 if Yes) |

**Table 2. List of weather variables considered in the analysis**

| | Variable | Scale | Definition/Unit |
|---|---|---|---|
| **Weather** | **Temperature** | Annual/Monthly | Temperature in °C (minimum, maximum, average) |
| | | Average Growing Season Temperature (GST, April to October) | $\sum_{d=1}^{n} \frac{[T_{max} + T_{min}]/2}{n}$ |
| | | Growing Degree- Days (GDD, April to October) | $\sum_{d=1}^{n} max\left[\frac{(T_{max} + T_{min})}{2} - 10; 0\right]$ |
| | | Huglin Index (HI, April to September) | $\sum_{d=1}^{n} max[(T_{mean} - 10 + T_{max} - 10)/2; 0] \times d$, with d=1.05 for Bordeaux |
| | | Biologically Effective Degree-Days (BEDD, April to October) | $\sum_{d=1}^{n} min\left(max\left[\frac{(T_{max}+T_{min})}{2} - 10; 0\right] \times d + TR_{adj}; 9\right)$, with d=1.05 for Bordeaux $TR_{adj} = \begin{cases} 0.25[T_{max} - T_{min} - 13]\ if\ [T_{max} - T_{min}] > 13 \\ 0\ if\ [T_{max} - T_{min}] < 13 \\ 0.25[T_{max} - T_{min} - 10]\ if\ [T_{max} - T_{min}] < 10 \end{cases}$ |
| | **Rainfall** | Annual/Monthly | Cumulative mm |
| | **Sunshine** | Annual/Monthly | Cumulative hours |
| **Extreme events** | **Hail** | Annual/Monthly | Number of days |
| | **Frost** | Annual/Monthly | Number of days with Tmin < 0 |
| **Climate variables** | **Temperature** | 30-year rolling deviation | $\frac{(T_{ave,year} - T_{ave,30\ rolling\ years})}{T_{ave,30\ rolling\ years}}$ in % |
| | **Rainfall** | 30-year rolling deviation | $\frac{(P_{year} - P_{30\ rolling\ years})}{P_{ave,30\ rolling\ years}}$ in % |
| | **Frost** | 30-year rolling deviation | $\frac{(F_{year} - F_{30\ rolling\ years})}{F_{ave,30\ rolling\ years}}$ in % |

**Table 3. Correlation of temperature indexes at Bordeaux-Mérignac weather station from 1970 to 2020**

| | BEDD | GST | GDD | HI | Tave | Tmin | Tmax | Sunshine |
|---|---|---|---|---|---|---|---|---|
| **BEDD** | 1.00 | | | | | | | |
| **GST** | 0.83*** | 1.00 | | | | | | |
| **GDD** | 0.81*** | 0.99*** | 1.00 | | | | | |
| **HI** | 0.75*** | 0.93*** | 0.93*** | 1.00 | | | | |
| **Tave** | 0.61*** | 0.83*** | 0.85*** | 0.87*** | 1.00 | | | |
| **Tmin** | 0.01 | -0.01 | -0.00 | -0.06*** | 0.27** | 1.00 | | |
| **Tmax** | 0.17*** | 0.61*** | 0.64*** | 0.62*** | 0.66*** | 0.01 | 1.00 | |
| **Sunshine** | 0.47*** | 0.49*** | 0.48*** | 0.55*** | 0.43*** | -0.24*** | 0.25*** | 1.00 |

*Key: *, ** and *** respectively denote significance at the 10%, 5% and 1% levels respectively.*

*Source: Own work, based on our computations on Météo France weather data 1970-2020.*

**Table 4. Summary statistics of wine-producing farms in the Bordeaux region in 2000, 2010 and 2020**

| | 2000 | 2010 | 2020 |
|---|---|---|---|
| **Vineyard area (ha)** | 23.26 (17.17) | 24.72 (19.27) | 28.89 (26.47) |
| **Wine production (hl)** | 1,311.74 (1,037.51) | 1,166.86 (1,012.96) | 1,187.90 (1,358.85) |
| **Wine yield (hl/ha)** | 55.40 (12.19) | 46.00 (13.80) | 37.69 (16.59) |
| **Wine revenue (€)** | 280,868 (348,522) | 260,425 (338,285) | 231,943 (320,434) |
| **Wine revenue (€/ha)** | 11,450.96 (11,450.74) | 10,582.77 (9,870.20) | 9,128.18 (11,580.75) |
| **Wine revenue (€/hl)** | 218.21 (215.70) | 255.94 (292.49) | 317.47 (670.62) |
| **Farm holder's age (years)** | 49.74 (10.47) | 49.52 (10.60) | 52.69 (9.99) |
| **Farm holder's higher general education (%)** | 0.79% (8.90%) | 8.19% (27.50%) | 8.15% (27.43%) |
| **Farm holder's higher agricultural education (%)** | 2.38% (15.30%) | 21.31% (41.06%) | 28.80% (45.40%) |
| **Total workforce on the farm (AWU)** | 4.31 (3.84) | 4.35 (4.08) | 4.04 (3.30) |
| **Total workforce on the farm/ha (AWU/ha)** | 0.17 (0.13) | 0.18 (0.13) | 0.14 (0.12) |
| **Irrigation (%)** | 6.34% (24.48%) | 4.91% (21.68%) | 8.15% (27.43%) |
| **Crop insurance (%)** | n.a. | 56.83% (49.66%) | 78.26% (41.35%) |
| **Retail selling (%)** | n.a. | 63.38% (48.30%) | 75.00% (43.41%) |
| **No pesticides (%)** | n.a. | 1.63% (12.73%) | 0.00% (0.00%) |
| **Turnover (€)** | 310,113 (353,898) | 275,446 (348,587) | 280,865 (327,335) |
| **EBITA (€)** | 96,266 (152,483) | 59,110 (112,476) | 20,952 (115,389) |
| **Net income (€)** | 54,023 (137,246) | 27,705 (110,840) | -21,521 (113,226) |
| **Net investment (€)** | 8,929 (55,191) | 7,907 (106,364) | -5,973 (57,465) |
| **Operating expenses (€)** | 252,908 (274,204) | 264,450 (339,051) | 312,976 (34,0918) |
| **Return on assets (%)** | 7.82% (11.11%) | 5.56% (10.64%) | -0.94% (13.16%) |

*Source: Own work, based on our computations on FADN data.*

*Key: The average is shown in plain characters and the standard deviation in brackets, n.a. denotes unavailable information.*

**Table 5. Results of the simultaneous equation modelling for years 2000-2020, seasonal indicators**

| | Wine yield (hl/ha) | Vineyard area (ha) | Wine revenue (€/ha) |
|---|---|---|---|
| **Vineyard area (ha)** | 0.0506*** | | -915.8838*** |
| **Wine yield (hl/ha)** | | | 94.6165* |
| **Average temperature (°C)** | -0.5583 | | |
| **Rainfall (mm)** | -0.0323*** | | |
| **Frost (days)** | -0.0742 | | |
| **Average temperature 30-year rolling deviation (%)** | | -21.4283** | |
| **Rainfall 30-year rolling deviation (%)** | | 1.9528 | |
| **Frost 30-year rolling deviation (%)** | | -0.0014 | |
| **Hail (days)** | -0.3242 | | |
| **Sunshine (hours)** | -0.0167 | | |
| **Farm holder's age (years)** | 0.0762** | | |
| **Farm holder's agricultural education (dummy)** | 1.3454*** | | |
| **Total workforce on the farm (AWU/ha)** | -9.4716*** | -31.3466*** | |
| **Irrigation (dummy)** | 2.0132* | | |
| **Insurance (dummy)** | | | 2125.3980*** |
| **Retail selling (dummy)** | | | 954.0529** |
| **No pesticides (dummy)** | | | 3245.0400* |
| **Net investment (€)** | -0.0004 | 0.0001*** | |
| **Operating expenses (€)** | | | 0.0452*** |
| **Year** | -0.3673*** | 0.4400*** | 133.9045*** |
| **Intercept** | 834.4112*** | 33.2832*** | 2525.7670*** |
| **Observations** | 3,521 | 3,521 | 3,521 |
| **Wal Chi2** | 337.99 | 240.35 | 1780.38 |
| **Prob > Chi2** | 0.0000 | 0.0000 | 0.0000 |
| **R2** | 0.0922 | 0.0650 | 0.07855 |

*Key: *, ** and *** respectively denote significance at the 10%, 5% and 1% levels respectively. Weather indicators are expressed on a seasonal basis (April to October).*

*Source: Own work, based on our computations on FADN data 2000-2020 and Météo France data 1970-2020.*

**Table 6. Results of the simultaneous equation modelling for years 2000-2020, monthly indicators**

| | Wine yield (hl/ha) | Vineyard area (ha) | Wine revenue (€/ha) |
|---|---|---|---|
| **Vineyard area (ha)** | 0.0486*** | | -916.2386*** |
| **Wine yield (hl/ha)** | | | 103.5634** |
| **Average temperature - May (°C)** | -0.8158** | | |
| **Average temperature - June (°C)** | -1.4119*** | | |
| **Average temperature - July (°C)** | -0.9369*** | | |
| **Average temperature - August (°C)** | 0.9829*** | | |
| **Average temperature - September (°C)** | 0.8727*** | | |
| **Rainfall – May (mm)** | -0.0378*** | | |
| **Rainfall – June (mm)** | -0.0806*** | | |
| **Rainfall – July (mm)** | -0.1270*** | | |
| **Rainfall – August (mm)** | 0.0100 | | |
| **Rainfall – September (mm)** | -0.0413* | | |
| **Frost – April (days)** | -0.1422 | | |
| **Frost – May (days)** | -4.9247** | | |
| **Average temp 3-year rolling deviation - May (%)** | | -9.7264* | |
| **Average temp 3-year rolling deviation - June (%)** | | -16.9010*** | |
| **Average temp 3-year rolling deviation - July (%)** | | -2.6204 | |
| **Average temp 3-year rolling deviation - August (%)** | | 11.2760* | |
| **Average temp 3-year rolling deviation - September (%)** | | 3.2923 | |
| **Rainfall 3-year rolling deviation - May (%)** | | 1.9528 | |
| **Rainfall 3-year rolling deviation - June (%)** | | -1.5285** | |
| **Rainfall 3-year rolling deviation - July (%)** | | -2.0978* | |
| **Rainfall 3-year rolling deviation - August (%)** | | -2.3660*** | |
| **Rainfall 3-year rolling deviation - September (%)** | | 2.4997*** | |
| **Frost 3-year rolling deviation - April (%)** | | -0.4409 | |
| **Frost 3-year rolling deviation - May (%)** | | -1.7433*** | |
| **Hail (days)** | 0.6204 | | |
| **Sunshine (hours)** | -0.0017 | | |
| **Farm holder's age (years)** | 0.0713*** | | |
| **Farm holder's agricultural education (dummy)** | 1.3951*** | | |
| **Total workforce on the farm (AWU/ha)** | -9.3607*** | -30.9748*** | |
| **Irrigation (dummy)** | 2.1180* | | |
| **Crop insurance (dummy)** | | | 2174.3250*** |
| **Retail selling (dummy)** | | | 1072.8920** |
| **No pesticides (dummy)** | | | 4432.7070* |
| **Net investment (€)** | 0.0004 | 0.0001*** | |
| **Operating expenses (€)** | | | 0.0452*** |
| **Year** | -0.4354*** | 0.3447*** | 184.2672*** |
| **Intercept** | 955.2431*** | 32.0928*** | 3543.2550*** |
| **Observations** | 3,521 | 3,521 | 3,521 |
| **Wal Chi2** | 576.11 | 277.44 | 1809.33 |
| **Prob > Chi2** | 0.0000 | 0.0000 | 0.0000 |
| **R2** | 0.1449 | 0.0718 | 0.0837 |

*Key: *, ** and *** respectively denote significance at the 10%, 5% and 1% levels respectively. Weather indicators are expressed on a seasonal basis (April to October) or on a monthly basis (when indicated).*

*Source: Own work, based on our computations on FADN data 2000-2020 and Météo France data 1970-2020.*

**Figure 1. Impact of weather and climate change on farm's area, yield and revenue**

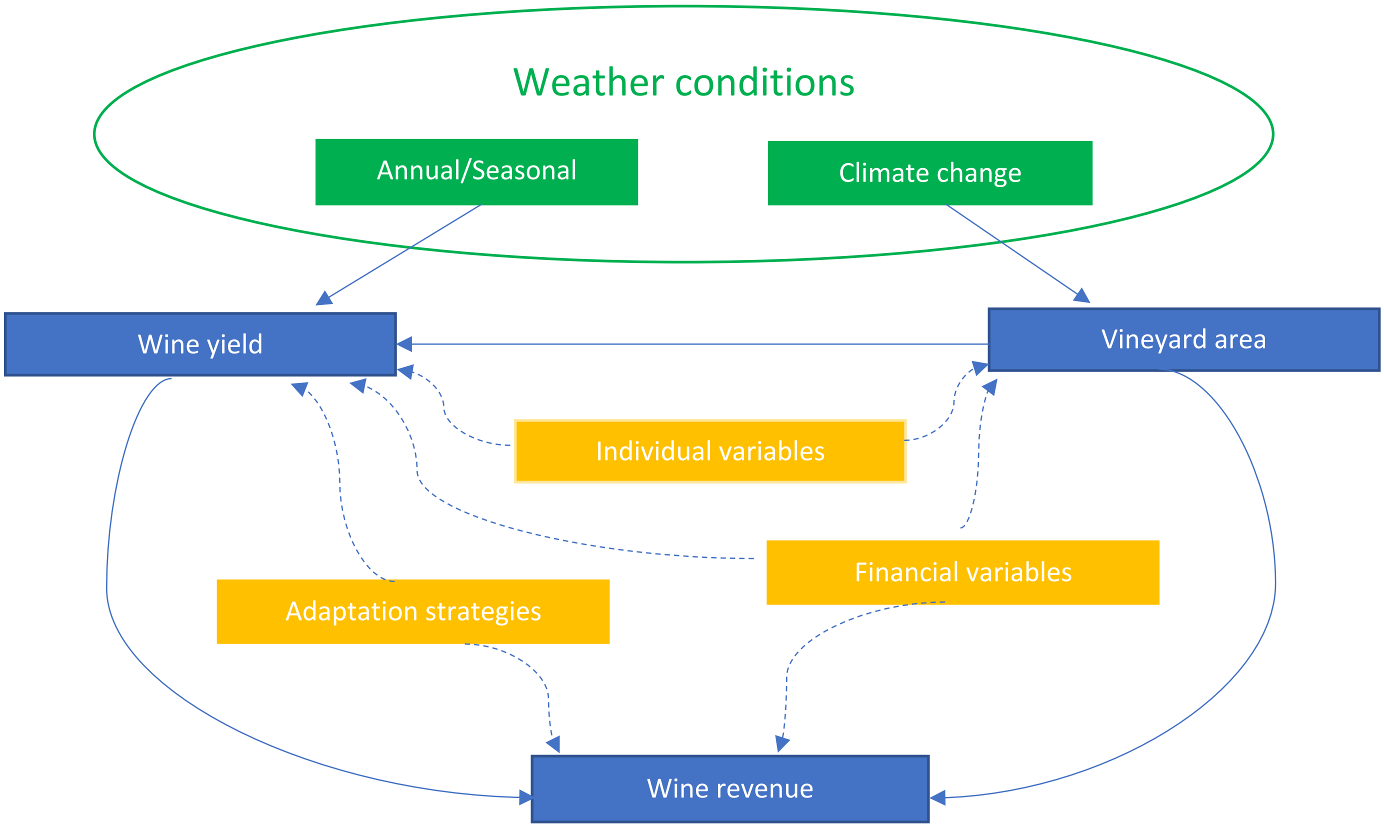
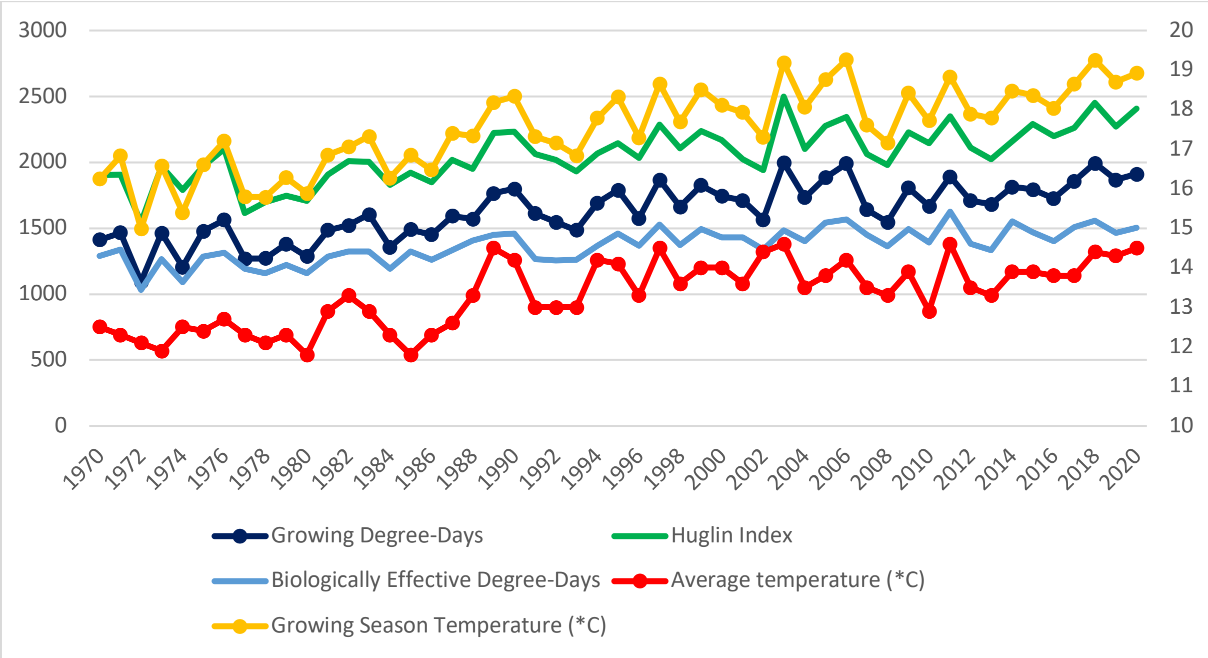


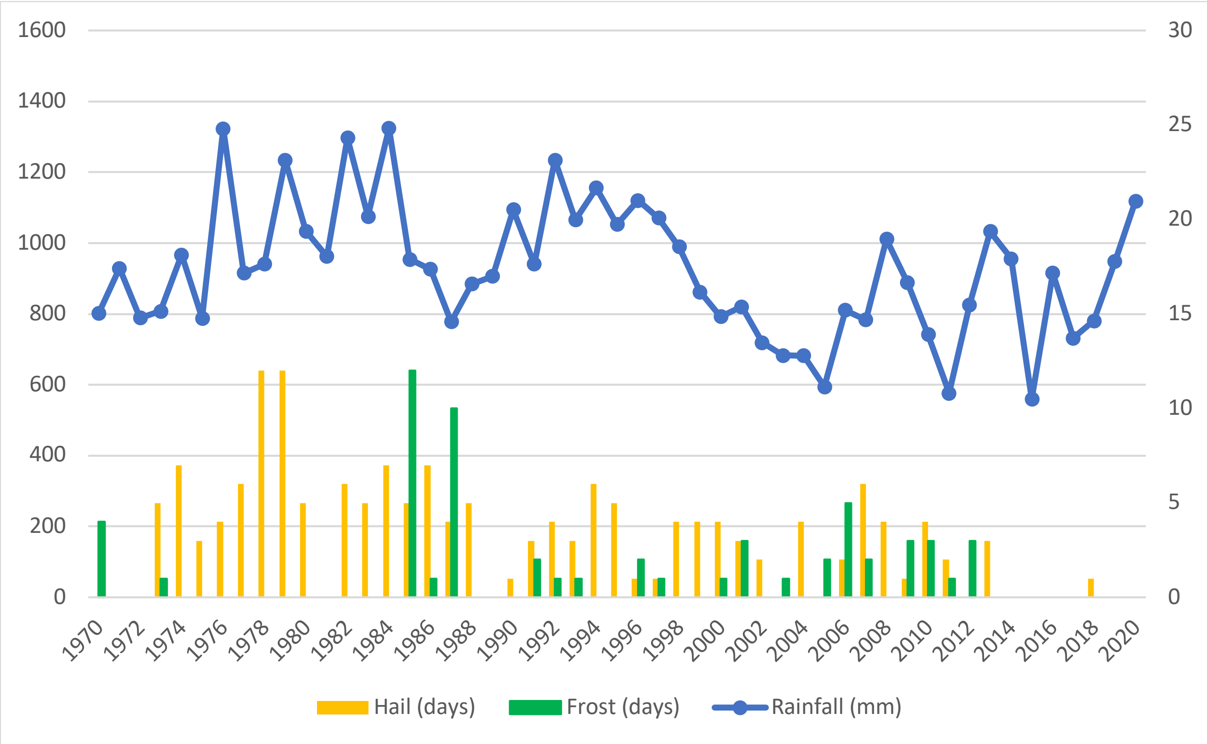
**Figure 2. Evolution of average temperature and other related indicators at Bordeaux-Mérignac weather station from 1970 to 2020**




*Key: Growing Degree-Days, Huglin Index and Biologically Effective Degree-Days can be read on the left scale. Average Temperature and Growing Season Temperature can be read on the right scale.*

*Source: Own representation, based on FADN data 1970-2020.*

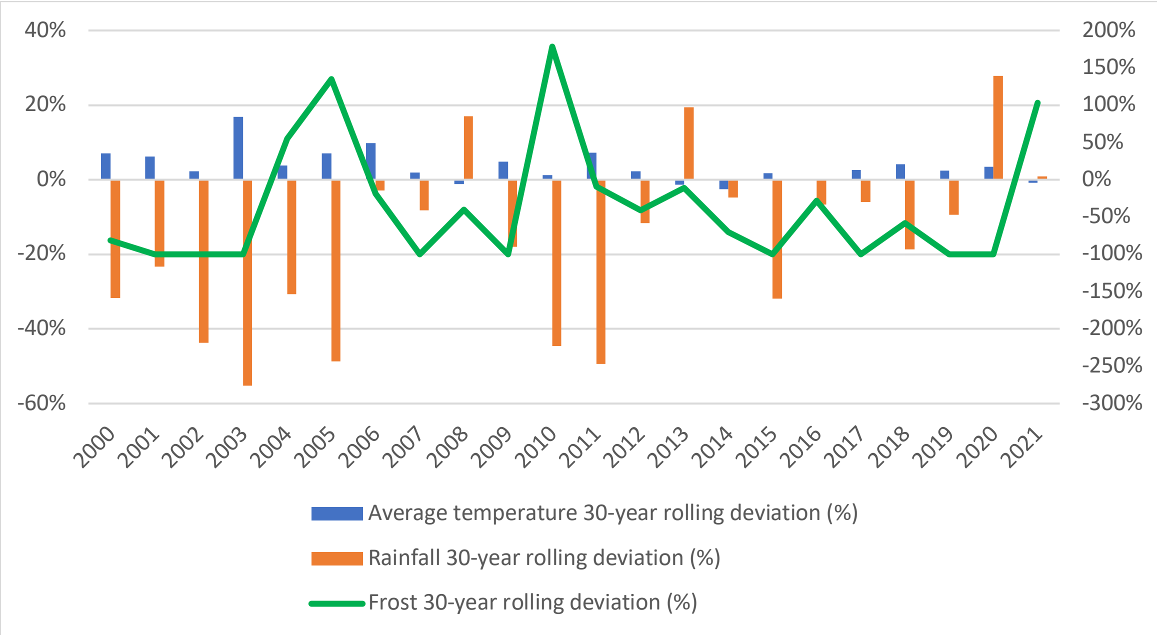
**Figure 3. Average rainfall and days of frost and hail at Bordeaux-Mérignac weather station from 1970 to 2020**




*Key: Rainfall can be read on the left scale. Hail and frost days can be read on the right scale.*

*Source: Own representation, based on FADN data 1970-2020.*

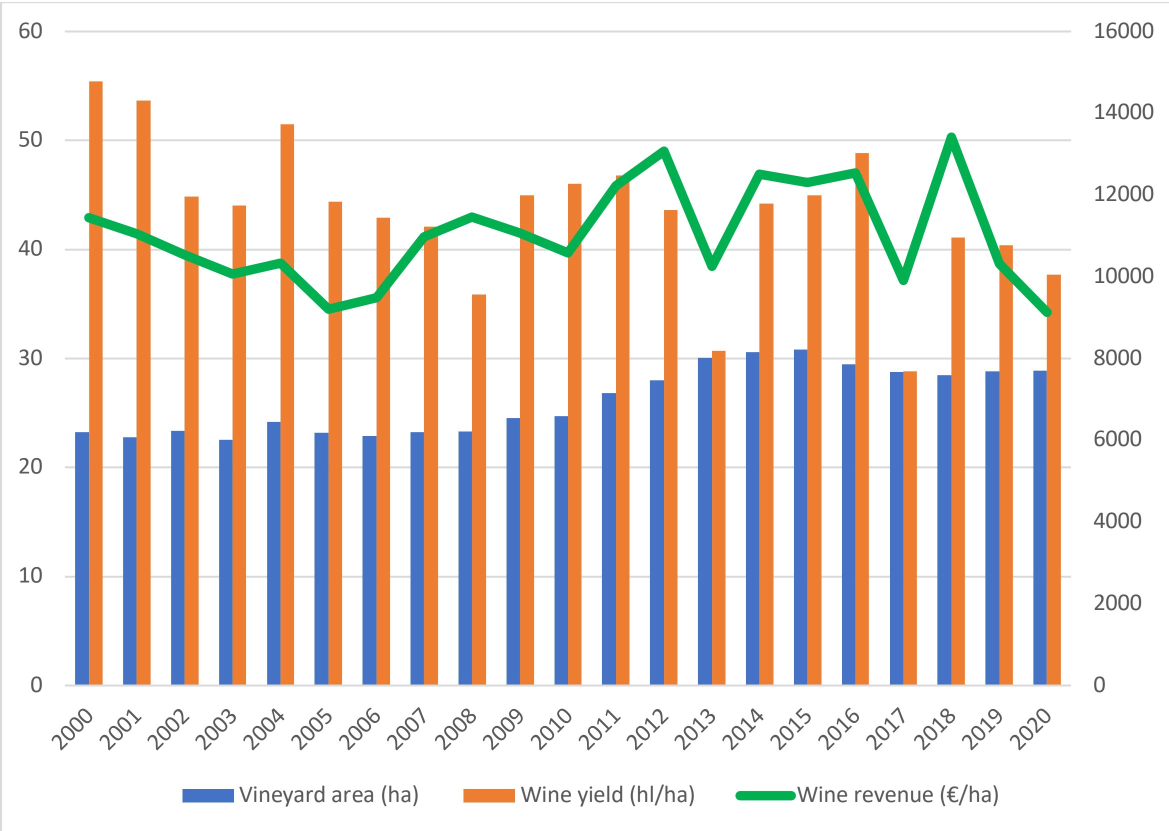
**Figure 4. Rolling deviations of temperature, rainfall and frost at Bordeaux-Mérignac weather station from 2000 to 2020**




*Key: The average temperature and rainfall 30-year rolling deviations can be read on the left scale. Frost 30-year rolling deviation can be read on the right scale.*

*Source: Own representation, based on FADN data 2000-2020.*

**Figure 5. Vineyard area, wine yield and wine revenue in the Bordeaux region from 2000 to 2020**




*Key: The cultivated area and wine yield can be read on the left scale. Wine revenue can be read on the right scale.*

*Source: Own representation, based on FADN data 2000-2020.*