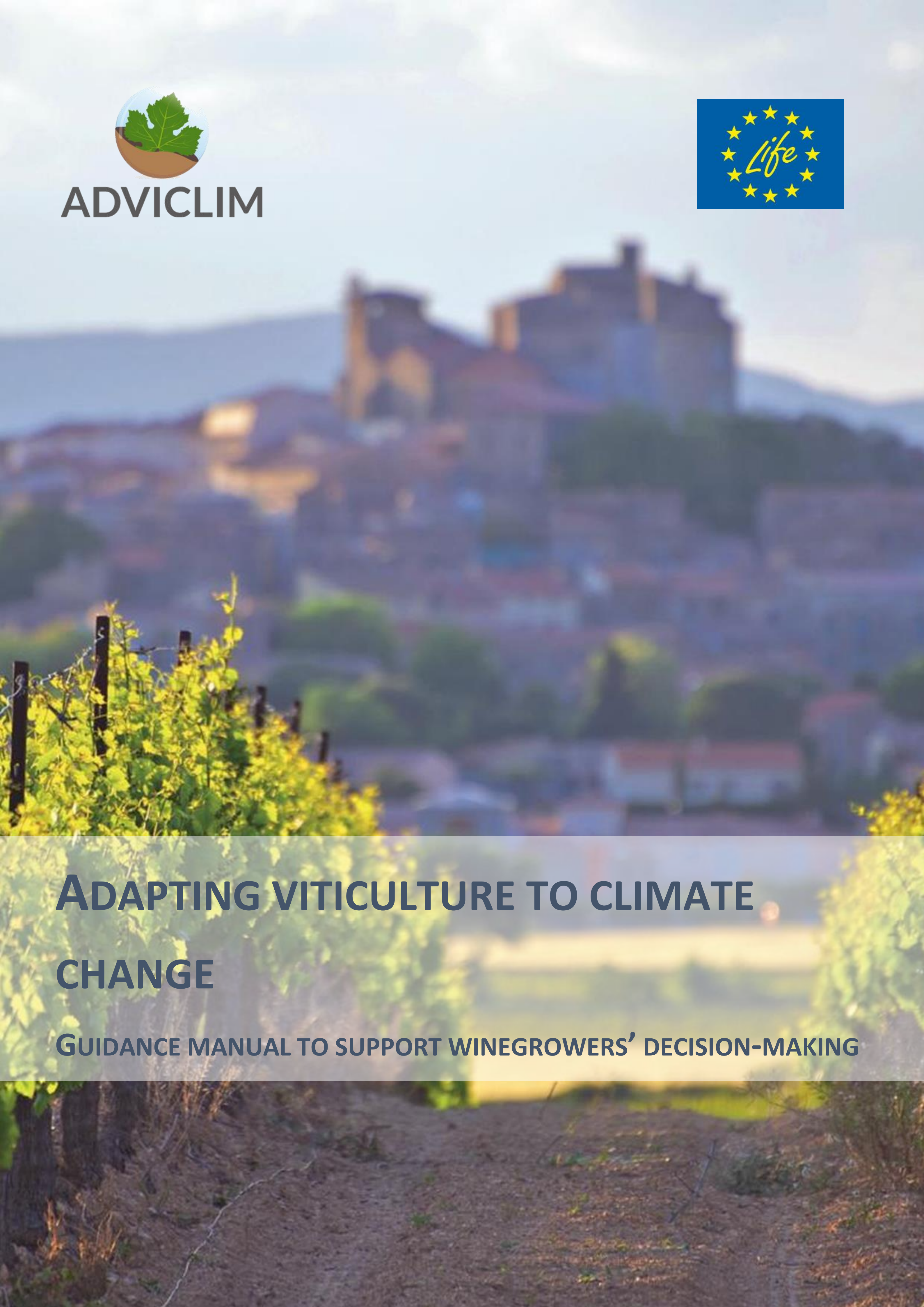

ADVICLIM

ADAPTING VITICULTURE TO CLIMATE CHANGE

GUIDANCE MANUAL TO SUPPORT WINEGROWERS' DECISION-MAKING

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The guidance manual can be found at http://www.adviclim.eu/

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FOREWORD

Across the earth, there is growing evidence that a global climate change is taking place. Observed regional changes include rising temperatures and shifts in rainfall patterns and extreme weather events. Over the next century, climate changes are expected to continue and have important consequences on viticulture. They vary from short-term impacts on wine quality and style, to long-term issues such as varietal suitability and the economic sustainability of traditional wine producing areas. As a result, the wine industry is facing many challenges, which includes adapting to these potential impacts, as well as reducing greenhouse gas emissions related to their activities.

In response to these challenges, the LIFE-ADVICLIM project has the objective to evaluate and develop local climate change adaptation and mitigation strategies. The measurement network and web platform of this project seeks to inform and assist winegrowers on climate change impacts, on rational adaptation scenarios and on greenhouse gas emissions related to their practices at the scale of their vineyard plots. These technologies are evaluated in many European wine growing regions (Figure 1), namely Bordeaux and Loire Valley (France), Sussex (England), Rheingau (Germany) and Cotnari (Romania). The region of Navarra in Spain is a non-official study area. These six regions represent the climatic diversity of European wine, ranging from the Mediterranean to Oceanic and Continental climates.

For more information on this project, visit www.adviclim.eu

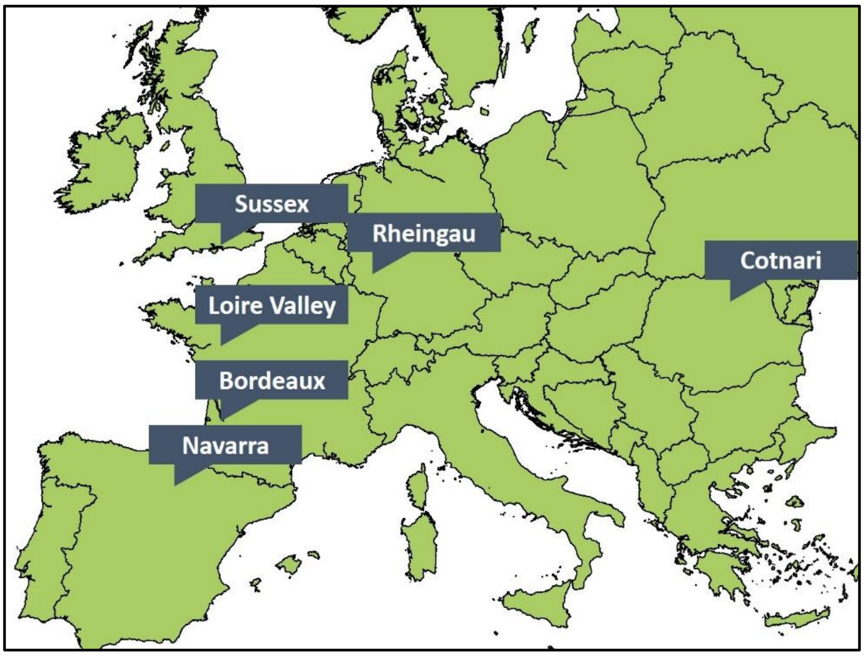
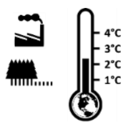


Figure 1: Position of the six European wine growing regions that are studied in the LIFE-ADVICLIM project.

INTRODUCTION

Within the LIFE-ADVICLIM project, the action B1 is particularly fitted to the development of local adaptation options to climate change European wine growing regions. By providing better understanding of actual and future agro-climatic potentials, it aims to assist winegrowers in building adaptation strategies to ensure the maintenance of wine quality and sustainable production. This manual aims therefore to inform on climate change and adaptation in viticulture, as well as to describe the modelling framework and process applied in this scientific project to address this issue. Indeed, while there are many management tools and solutions that hold great potential, there is little guidance on how viticultural practices should be undertaken at different temporal (short to long term) and spatial scales (local to regional level) in response to a changing climate.

The guidance manual is divided into **three parts**:



PART 1: The first part provide a general introduction of climate change in the viticulture sector. The goal is to give insights on global and regional climate changes, the impacts already observed on grape and wine production and the key issues associated with future climate impacts.

PART 2: The second part aims to inform winegrowers on potential adaptation strategies to climate change. In this context, it seeks to present some guidelines on identifying and performing adaptation measures at different temporal and spatial scales.

PART 3: The third part deals with the modelling framework used in action B1 of the LIFE-ADVICLIM project. By applying modelling techniques and tools, the action B1 aims to evaluate, identify and prioritise rational adaptation strategies at local vineyard scales.

ABOUT THIS MANUAL

This manual focus on the adjustment of viticultural management practices and decision-making in response to climate change at the vineyard level. It has been developed on the basis of scientific research and many field observations. However, the manual is not intended to be a definitive guide to management planning, but meant to generate knowledge and communication among local actors and stakeholders in European wine growing regions.

PART 1

CLIMATE CHANGE IN THE VITICULTURE SECTOR

Introduction

For most wine growing regions, significant trends in regional climates have been observed. At the same time, important changes in grapevine phenology and grape composition have occurred, with the latter leading to altered alcohol levels and sensory profiles. Although changes in grapevine behaviour are partly attributed to evolving practices, recent climate changes, in particular increasing temperatures, have been major causal factors. As a result, future climate changes are very likely to have key effects on wine quality and style, which over the long term may cause geographical shifts in suitable grapevine varieties and production areas. A changing climate is therefore one of the major environmental and socio-economic issues facing sustainable viticultural development and production over the next century.

VITICULTURE AND CLIMATE

The grapevine is cultivated over a wide range of climate conditions, where its fruit is primarily used for winemaking. As a result, viticulture is one of the most climate sensitive sectors to short- and long-term climate variations

- Firstly, a wine growing region’s long-term climate structure largely determines its grape growing and winemaking potential.
- Secondly, short-term climate variations are key factors influencing seasonal grape and wine production (i.e. quality and quantity).

General understanding of contemporary climate change

The earth is warming. Climate records sufficiently exhaustive demonstrate that warming affects almost the entire earth’s surface (Figure 2). Over the past century and a half, the Earth's average temperature has increased by 0.85°C.

The rate of global warming is unprecedented. Since the 1950s, the increase in temperature has accelerated rapidly, where each of the last three decades has been successively warmer than all the previous decades.

The change in rainfall is very variable. In general, rainfall amounts have increased at the mid to high latitudes of the northern hemisphere. At the subtropical level, rainfall has declined. Rainfall has increased in South America, northern Europe, and northern and central Asia, while decreasing in the Sahel, the Mediterranean regions and Southern Africa. It seems that wet regions are wetter and dry regions drier as the planet warms.

The world is experiencing more extreme weather. Although it is difficult to perceive a significant increase in extreme events, trends show a change in the frequency and intensity of these events (e.g. number of cold days, warm days).

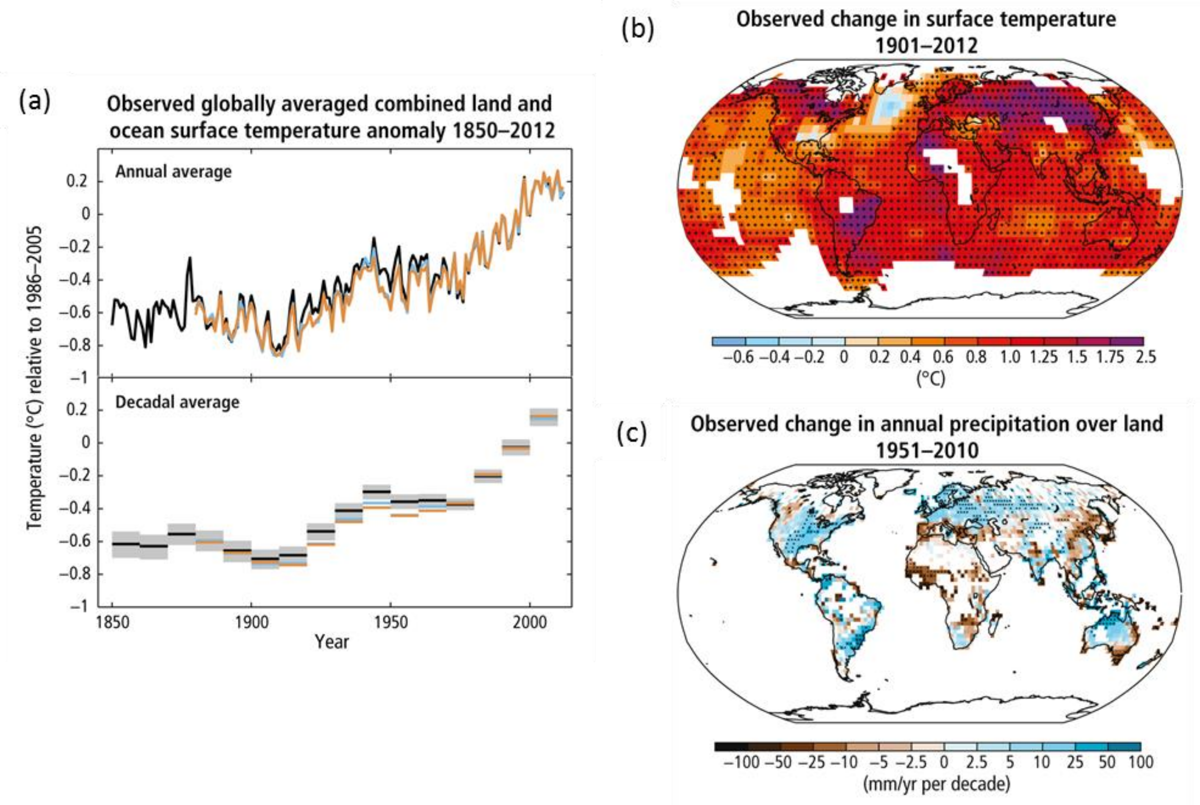


Figure 2: (a) Observed globally averaged combined land and ocean surface temperature anomalies (relative to the mean of 1986 to 2005 period, as annual and decadal averages); (b) Map of the observed surface temperature change, from 1901 to 2012; (c) Map of observed precipitation change, from 1951 to 2010 (Source: IPCC 2014).

KEY CLIMATE DEFINITIONS

Climate: The atmospheric conditions at a particular place in terms of temperature, humidity, wind speed, cloudiness and rainfall over a long period of time (generally 30 years). Weather refers to day-to-day variations in atmospheric conditions.

Climate variability: The natural variation in climate from year-to-year (i.e. over time) or across geographical areas (i.e. over space).

Climate change: Any significant change in the state of climate that lasts for an extended period of time, typically decades, whether due to natural causes or human activities.

Global warming: Long-term increase in the Earth's average temperature.

Climate change impacts: The effects of a changing climate on physical, biological or human systems.

Source: IPCC 2014

Current climate change is caused by natural and human processes. In comparison with past climate changes, current climate changes are particularly attributed to increasing greenhouse gas emissions. Rising greenhouse gases are trapping more of heat and causes the Earth to warm.

Climate change impacts are already occurring. There is a widespread evidence that climate changes have caused impacts on physical, biological and human systems on all continents and across the oceans. Evidence of observed impacts is strongest and most comprehensive for natural systems (e.g. water resources, sea levels, biodiversity).

Climate change in wine growing regions

Before the end of the 20th century, little work had been done on studying climate change and its impacts on grape and wine production. However, over the last few years many studies have been conducted, contributing to the development of the current understanding of climate change impacts in wine growing regions. The main observations are:

- Across wine growing regions, climate change has essentially resulted in regional warming, with geographical variations in its speed and magnitude.

- No significant change in rainfall patterns were observed. However, the amount of water supply to grapevines has evolved, resulting from a greater variability in seasonal rainfall and an increase in evapotranspiration rates.

- The rise in mean regional temperatures during the growing season has led to a sharp increase in the classifications of bioclimatic indices (Figure 3).

BIOCLIMATIC INDICES

Bioclimatic indices are a useful zoning tool, defining a region's ability to produce grapes, varietal suitability, etc. The two main indices used in viticulture are the Winkler and Huglin Indices. The former refers to the concept of growing degree-days, which is calculated as the sum of daily mean temperatures above 10°C for the period of April to October in the Northern Hemisphere. The base temperature of 10°C refers to the minimum temperature necessary for grapevine physiological activity. The interest in using the Winkler Index is that the cumulated heat is strongly correlated with grapevine phenology. The Huglin Index differs, as it is the sum of the mean and maximum temperature above 10°C from April to September in the Northern Hemisphere. It gives greater weight to daytime temperatures, when most vine development takes place and is therefore strongly correlated with berry composition at harvest.

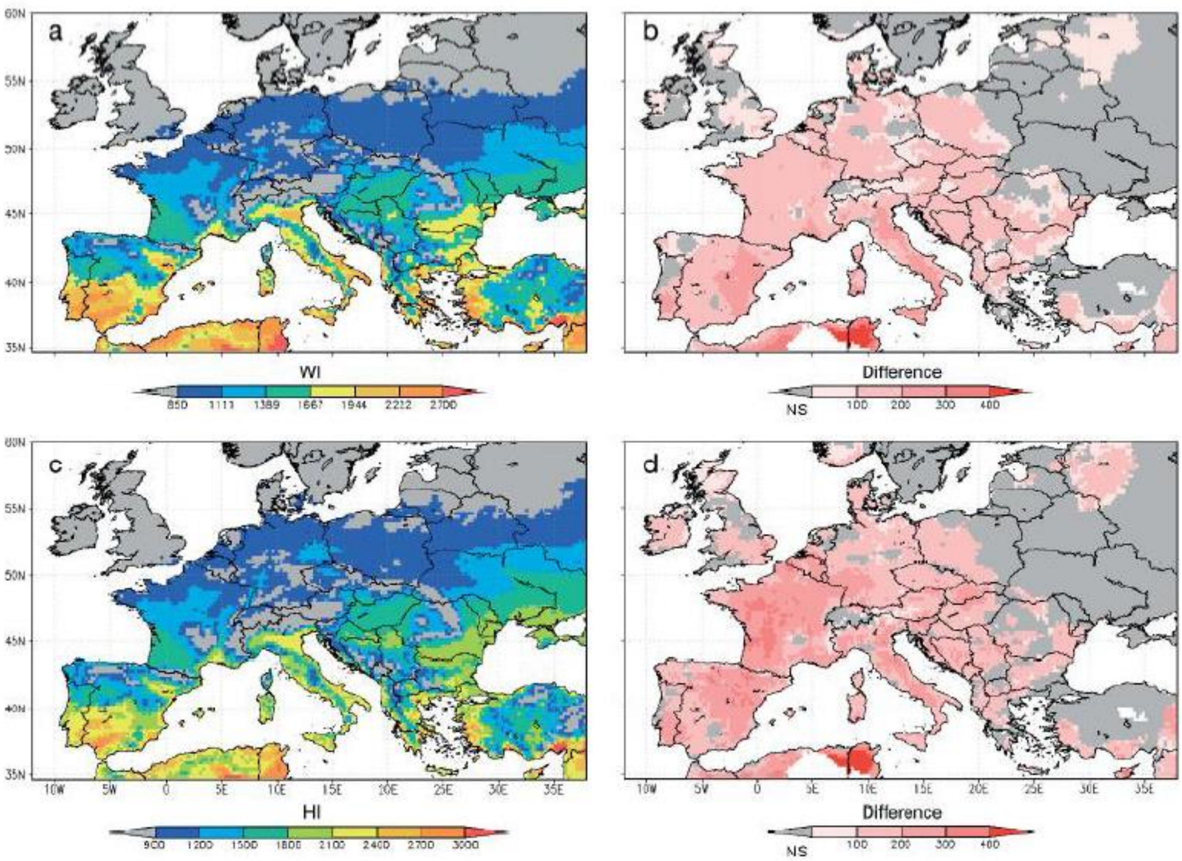


Figure 3: Mapping of the Winkler and Huglin indices in Europe for the period 1950 to 2009 (left) and the difference between the periods 1980-2009 and 1950-1979 (right) (Source : Santos et al. 2012).

- Due to regional warming, the thermal conditions characterizing northern latitude wine growing regions are more favorable for grape and wine production. However, some wine growing regions (e.g. in Southern Europe) have reached or even exceeded their optimum thermal conditions for the varieties currently grown there.

- Warming has also led to the emergence of new wine growing regions (e.g. England or even Sweden).

- The majority of the grape varieties show an earlier appearance in their phenological stages (bud break, flowering, and veraison) and the date of the onset of grape harvest. In general, phenological stages are two weeks earlier (Figure 4a).

- As grape ripening is taking place under warmer conditions, significant changes have occurred in grape composition. Grapes contain more sugar and less organic acids, which results in higher pH (Figure 4b).

- Changes in grape composition have also led to increased alcohol levels and altered wine sensory profiles.

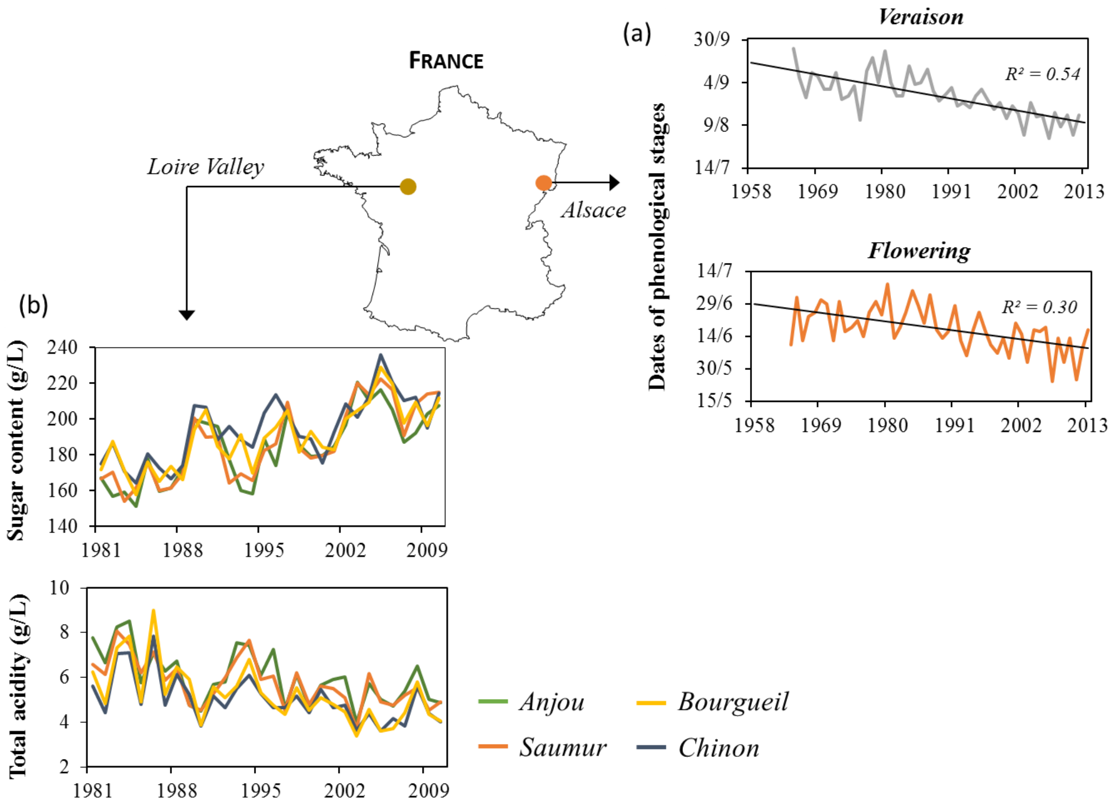


Figure 4: (a) The trend in the date of flowering and veraison for the grapevine variety Riesling cultivated in the wine growing region of Alsace, France (Source: http://www.developpement-durable.gouv.fr); (b) the change in the content of sugar and total acidity for the grapevine variety Cabernet franc, cultivated in the Loire Valley and more specifically in the wine producing areas of Anjou, Saumur, Bourgueil and Chinon (Source: Neethling et al. 2012).

Future climate changes and expected impacts

On the basis of current understanding of contemporary climate change, continued emission of greenhouse gases are expected to cause further warming, increasing the likelihood of severe and irreversible impacts for people and ecosystems.

Compared to historical periods from 1986 to 2005 (Figure 5), the increase in mean global temperatures for the period from 2081 to 2100 are likely to be in the range of:

- +0.3°C to +1.7°C (RCP2.6)
- +1.1°C to +2.6°C (RCP4.5)
- +1.4°C to +3.1°C (RCP6.0)
- +2.6°C to +4.8°C (RCP8.5)

According to the most optimistic scenario (RCP 2.6), the temperature rise should remain below the 2°C in 2100, which is the threshold considered critical for the expected impacts. Conversely, if greenhouse gas emissions continue at the same rate as at present, the RCP 6.0 scenario and in particular the RCP 8.5 scenario foresee a strong increase in temperature, exceeding the threshold of 2°C. Similarly, warming will continue to exhibit inter annual to decadal variability and as a result, climate change may only be observable after 2030. Concerning rainfall patterns, as observed in the 20th century, there is great temporal and spatial variability. The different scenarios illustrate that the average annual rainfall total will increase in the high latitudes, whereas they will decrease in the arid subtropical regions.

CLIMATE PROJECTIONS

Since climate change and its effects are already perceptible, climate projections are needed to understand the expected impacts and help inform adaptation planning and policy. To perceive future climate changes, projections of greenhouse gas emissions vary over a wide range, depending on both socio-economic development and climate policies. The IPCC (Intergovernmental Panel on Climate Change) proposes four scenarios of increasing global mean temperatures for the end of this century. The most optimist scenario (RCP 2.6) foresees that the emissions will be decreased drastically in a few decades, while the most pessimist scenario (RCP 8.5) is an extreme scenario without any decreases. Two intermediate reduction scenarios were also added (RCP 4.5, RCP 6.0).

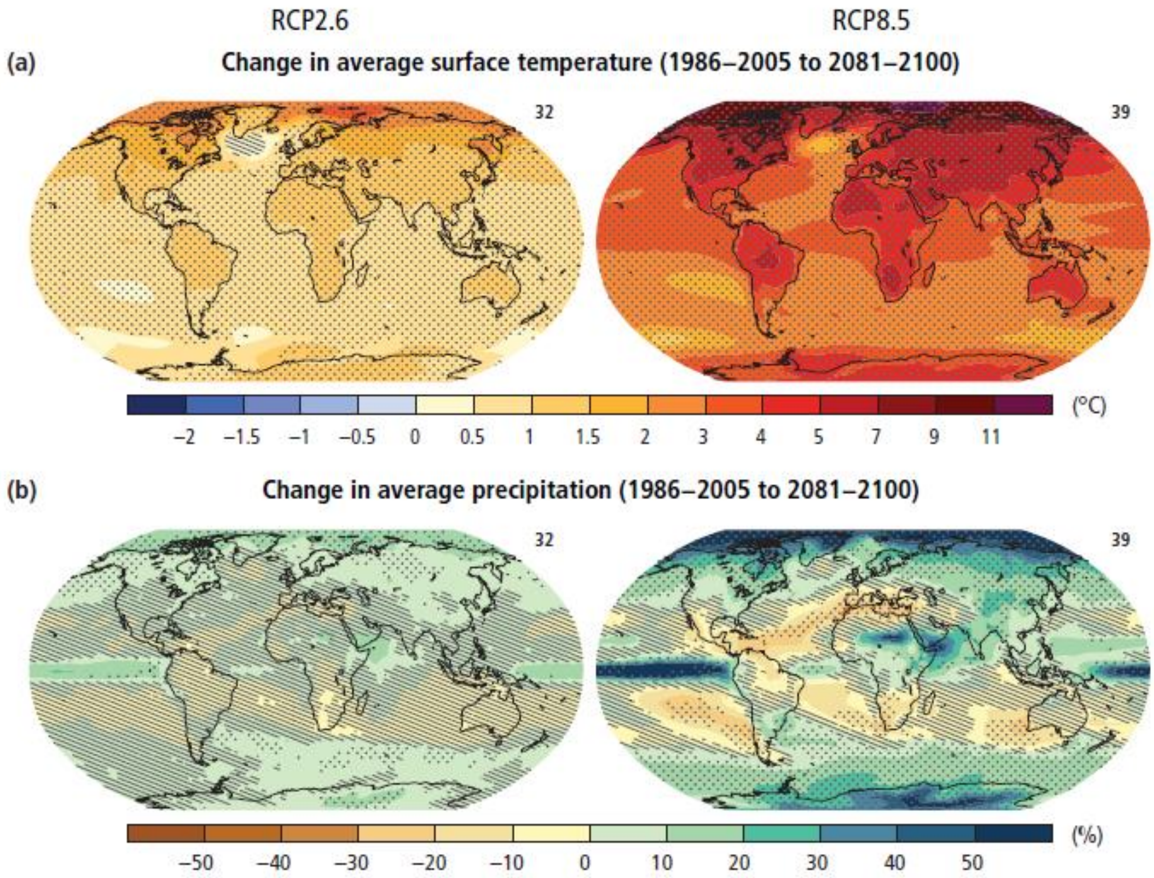


Figure 5: Change in average surface temperature (a) and change in average precipitation (b) based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios. The number of models used to calculate the multi-model mean is indicated in the upper right corner of each panel (Source: IPCC 2014).

EXPECTED CLIMATE CHANGES AND IMPACTS

- Contemporary climate change will continue through the 21st century
- Temperatures are likely to continue to rise (from 1.0°C to 3.7°C)
- Precipitation patterns are expected to continue to change
- Extreme weather events will likely become stronger and more intense
- Grapevine phenology is expected to advance significantly
- Wine quality and style are likely to be altered
- Climate change will bring both risks and opportunities in the wine industry

With predicted warming in annual and seasonal temperatures, important changes in temperature-based indices are expected over the 21st century. Relative to the recent past (1986-2005), the projected increases in the near (2031-2050) and far future (2081-2100) are illustrated in Figure 6. These results are for the wine growing regions in Europe, studied in the LIFE-ADVICLIM project. For example, according to the Huglin Index:

- The Loire Valley region is likely to shift from a “cool” to a “temperate” climate class in the near future, while to a “warm” or “very warm” climate class in the far future. To that end, this region may evolve from a suitable climate for early ripening varieties to a climate more suitable for late ripening varieties.

As mentioned before, temperature based indices are indicators of the viticultural potential of a region. Consequently, a changing climate is expected to bring about many consequences on grapevine phenology and grape productivity. As a result, future climate changes are very likely to have key effects on wine quality and style over the short term, which over the long term may cause geographical shifts in suitable grapevine varieties and production areas. However, these consequences are likely to vary strongly according to the type of grapevine variety cultivated, the type of soil on which vines are planted and grown, and the type of wine produced. Expected climate change impacts will also vary according to the nature of adaptation taking place at farm to plot level of winegrowers.

GRAPEVINE PHENOLOGY

Grapevine phenology refers to the timing of its growth stages, which are very climate sensitive. A grapevine’s phenological characteristics are very important for viticultural planning and decision making. Indeed, varieties should be well adapted to their local climate conditions to ensure optimal growth and ripening. If harvest occur to early, grapes are rich in sugar, have low acidity levels, promoting unbalance wines. Instead, when ripening occurs to late, grapes have high acidity and low sugar contents, with unripe aromas. In the Northern Hemisphere, optimal ripening generally occurs during the month of September, when days are still warm and sunny, with cooler nights.

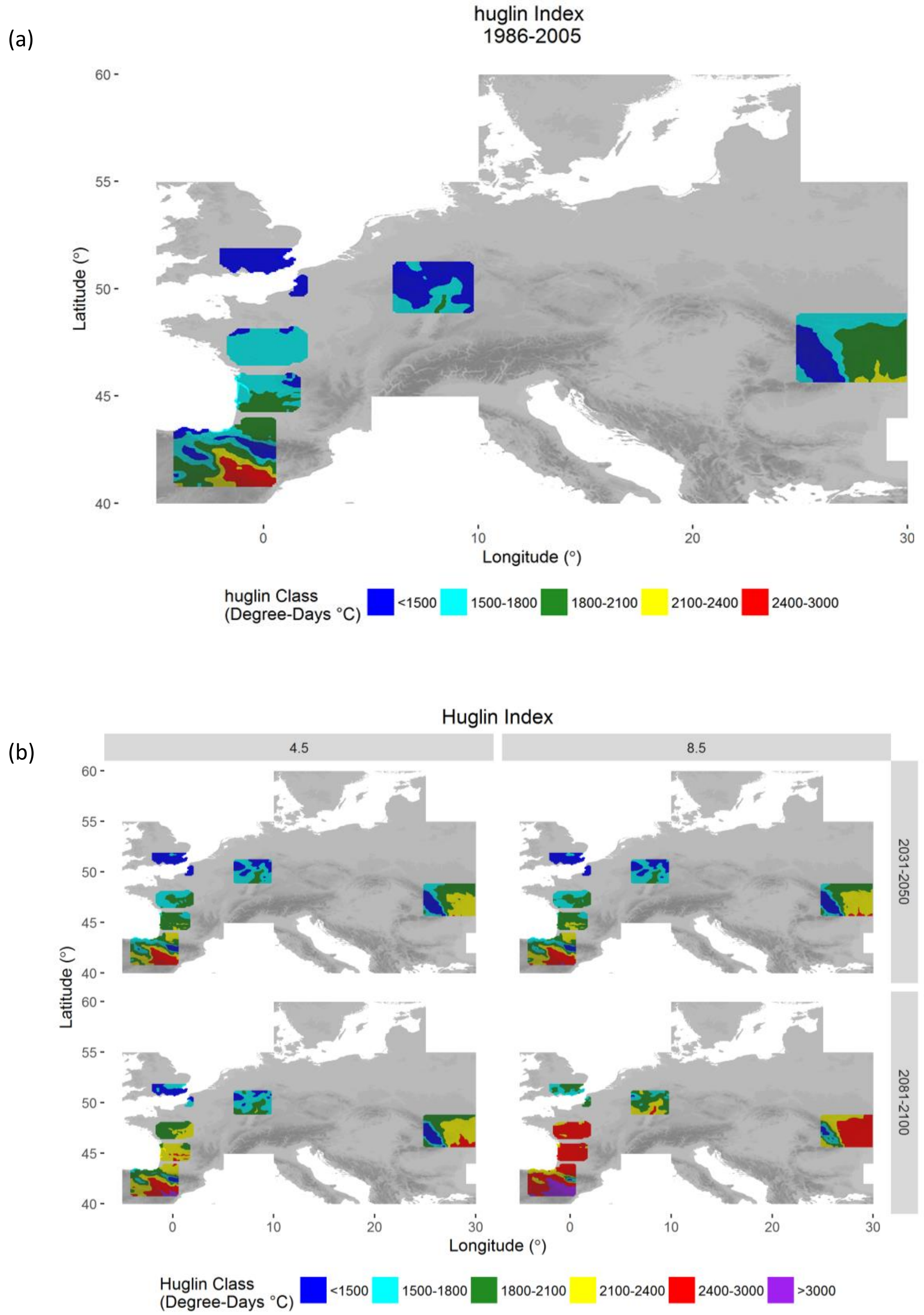


Figure 6: (a) Mapping of the Huglin Index in 6 European wine growing regions for the period 1986 to 2005 and (b) the changes expected in the Huglin Index for the period 2031 to 2050 and 2081 to 2100 according to the climate scenarios of RCP4.5 and RCP8.5 (Data source: EURO-CORDEX).

For more information on climate change and viticulture, please read:

- Jones GV, Webb LB (2010) Climate change, viticulture, and wine: challenges and opportunities. J Wine Res 21: 103–106

- Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA (2012) An overview of climate change impacts on European viticulture. Food Energ Secur 1:94–110

- IPCC (2014) Climate Change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri RK, Meyer LA (eds.), IPCC, Geneva, Switzerland

- Mozell MR, Thach L (2014) The impact of climate change on the global wine industry: challenges & solutions. Wine Econ Policy http://dx.doi.org/10.1016/j.wep.2014.08.001

- Ollat N, Touzard JM (2014) Impacts and adaptation to climate change: new challenges for the French wine industry. J Int Sci Vigne Vin. Special issue climate change: 77-80

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Part 2

Implementing adaptation strategies in response to climate change

Introduction

Adaptation to climate change is a major challenge facing the viticulture sector. Temporally, adaptation strategies and policies have to address potential impacts in both the short- and long-term, whereas spatially, place-based and context-specific adaptations are essential. In order to overcome these issues and help inform decision-making, this second part aims to present some guidelines on identifying and performing adaptation measures to climate change. It should be noted that as each wine growing region consist of unique contexts, knowledge and understanding of the contextual factors and their interaction with the regional climate are essential to identify and prioritize adaptation initiatives at different temporal and spatial scales.

Potential adaptation measures to climate change

Over the next century, winegrowers will likely be confronted by increasing temperatures and changing rainfall patterns that will have important impacts on mainly two aspects of grape growing:

- Grapevine phenology: As growing stages are expected to advance, a shifting ripening period to warmer conditions in the summer will affect grape composition (e.g. sugar and acidity levels) and aroma compounds.
- Soil water availability: Grapevines are likely to grow under more water stress conditions because of rising temperatures, higher evapotranspiration rates and changing rainfall patterns. These conditions are expected to have key influences on grape quality and yield.

To that end, there are several strategies that winegrowers can employ. Table 1 illustrate the possible types of climate change adaptation responses where their impacts on the issues of grapevine phenology and soil water availability are displayed.

Table 1: Examples of possible types of adaptation responses to the continuation of climate change for a given plot (adapted from Van Leeuwen et al. 2016).

Adaptation measures	Effect on delaying grape ripening	Adaptation measures	Water stress Intensity
Delaying pruning date	3-5 days	Cover crop species	Weak
Increasing trunk height	3-5 days	Soil tillage techniques	Weak
Reducing leaf area/ fruit weight ratio	5-12 days	Mulching techniques	Weak
Choice in rootstock variety	3-6 days	Trellising system	Medium
Clonal selection	3-8 days	Choice in rootstock variety	Medium
Choice in grapevine variety	10-25 days	Irrigation	Strong

These strategies range from short-term adjustments (e.g. in harvest management practices) to long-term adjustment, such as in varietal selection. In response to increasing temperatures and changing rainfall patterns, they vary therefore in nature and effectiveness, where long-term measures in the choice in grapevine variety and the use of irrigation are the most effective (Figure 7). However, these long-term measures will likewise induce the greatest changes in wine style and quality.

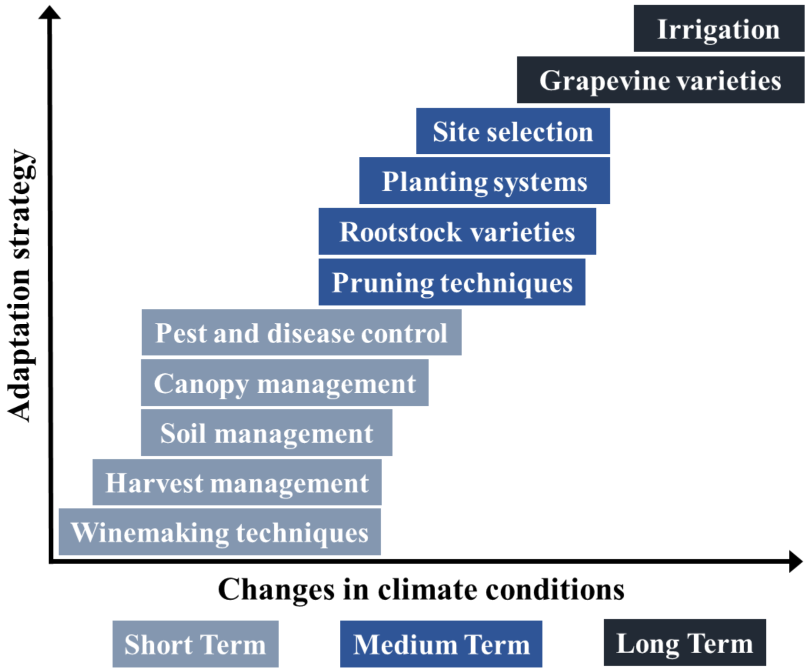


Figure 7: Representation of different adaptation strategies to changes in climate conditions over the short, medium and long term (results are based on the responses of winegrowers from Saumur Champigny, and adapted according to the framework proposed by Nicholas and Durhan, 2012).

For more information on climate change adaptation in viticulture, please read:

- Mozell MR, Thach L (2014) The impact of climate change on the global wine industry: challenges & solutions.
- Nicholas KA, Durham WH (2012) Farm-scale adaptation and vulnerability to environmental stresses: insights
- Van Leeuwen C, Darriet P (2016) Impact of climate change on viticulture and wine quality. J. Wine Econ., 11, 150-167.
- Quénol H (2014) Changement climatique et terroirs viticoles. Lavoisier Editions Tec & Doc, Paris.

Short term adaptation options

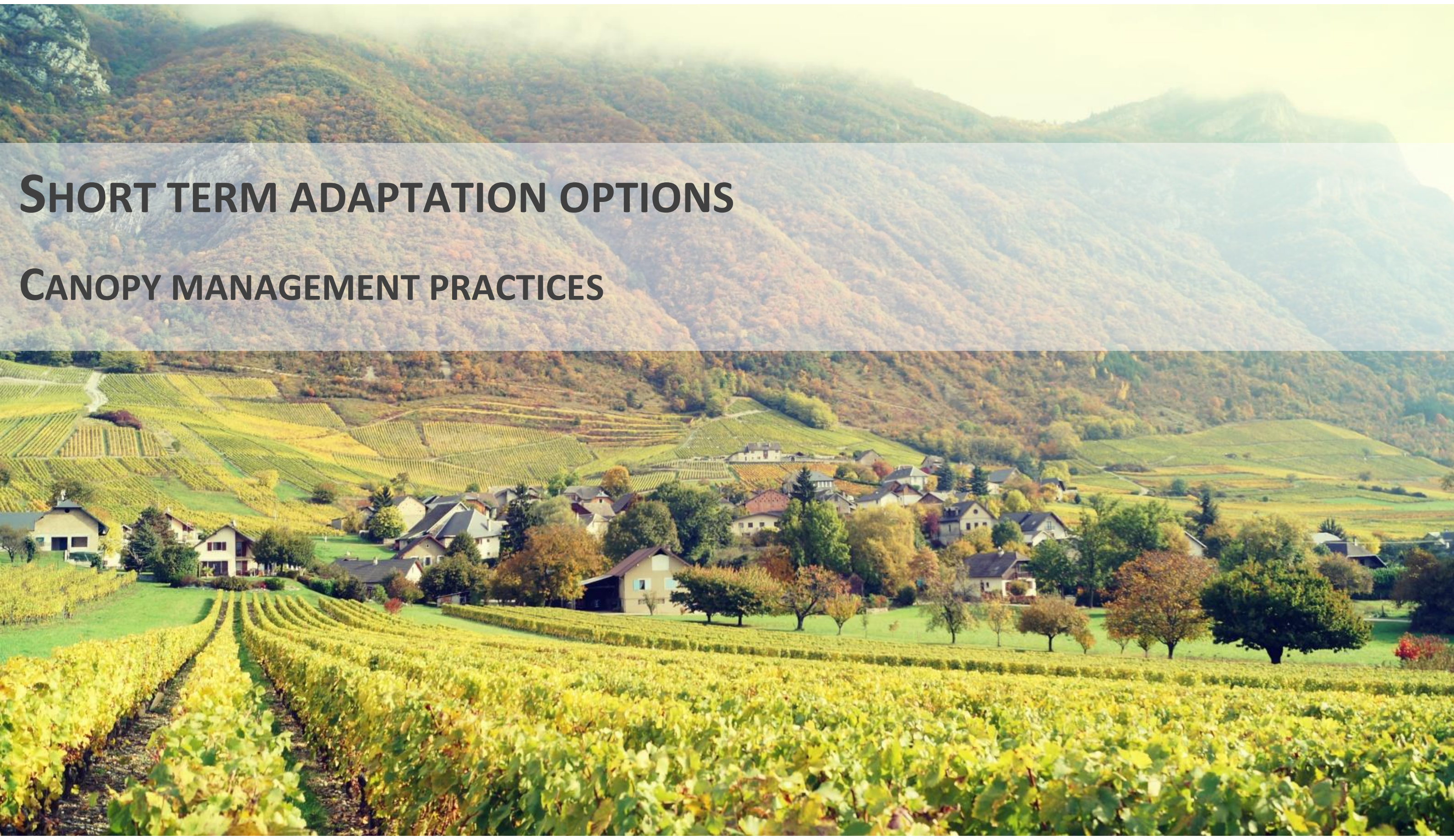
Harvest management and Winemaking practices

In the context of climate change, the first level of adaptation concerns two annual practices that have a high reactivity to manage seasonal grape composition.

- Firstly, depending on the evolution of grape ripening, coinciding climate conditions and grey rot risks, adjustments in harvest management practices allow to manage the annual variability in grape composition.

- Secondly, once harvested, grapes are transported to the wine cellar where winemaking practices are implemented to process grape composition and produce quality wine.

Over recent years, these two practices have evolved significantly, and in the short-term, it is reasonable to assume that harvest management and winemaking innovations will continue. In order to deal with the impacts of climate change, and maintain a correct grape composition, harvest timing and temperature control will become essential. For the former, an adaptation solution is to advance harvest dates, while for the latter, the temperature of freshly picked grapes should be as low as possible to limit biochemical alteration processes. Grapes may also be picked at night with mechanical harvesters and transported in refrigerated trucks when long distance trips are necessary.



SHORT TERM ADAPTATION OPTIONS

CANOPY MANAGEMENT PRACTICES

Short term strategies in canopy management practices required to delay the development cycle of the grapevine within a season, in particular the date at which the ripening process starts (i.e. véraison) include :

- Late spur-pruning
- Increasing vine trunk height
- Trimming shoots or removing leaves to reduce the leaf area to fruit weight ratio

For example, spur-pruning vines late in the winter (at about the time of bud-break) can delay the onset of bud-break by eight to 11 days when compared to traditional mid-winter pruning. This can in turn result in a delay in flowering and véraison dates of up to four or five days. While this may work, it means that vines would need to be pruned in a very limited time frame which may limit its application to small producers and not be feasible for large scale operations. Also, trimming the canopy of vines shortly after fruit set, to reduce canopy area to less than 0.75 m2/kg fruit can increase the time from flowering to véraison date by approximately 5 days. Shading bunches either by changing vine management to increase leaf cover may result in significantly lower fruit temperatures, and an increase in fruit malic acid concentration and titratable acidity at harvest. While these practices can be adopted, depending on the vine development of any particular season, the effect on phenology is likely to be small, when compared to the long-term strategies.

SHORT TERM ADAPTATION OPTIONS

SOIL MANAGEMENT PRACTICES

Soil management practices are used to better manage the grapevine's water supply, control its vigour and avoid soil erosion. These practices include mainly:

- Soil tillage techniques
- Cover cropping species

In Europe, with pressure from environmental measures, new tools for soil tillage have emerged in recent years to propose alternatives to chemical weed control. This has been replaced by shallow soil management or grass cover according to soil types and climatic conditions.

The shallow tillage of the soil makes it possible to limit the problems of summer drought by limiting the evaporation of the soil. For its part, grass cover has provided solutions during important rainy periods by improving the soil's bearing capacity and limiting the vigour of the vine. These practices will evolve according to the episodes of drought and heat waves.

Other methods include mulching techniques (based on plant fibres, for example). This practice aims at limiting the use of herbicides under the row, but it is also studied for its potential impact on the reduction of soil evapotranspiration to avoid severe water stresses to the grapevine during episodes of drought.

SHORT TO MEDIUM TERM ADAPTATION OPTIONS

MANAGEMENT OF FROST RISKS

The close relationship between local topography and frost damage means that frost protection methods varies spatially and are either passive or active.

- Passive protection includes indirect methods (e.g., site selection, pruning techniques) carried out in advance to reduce the vineyards' susceptibility to frost damage.
- Active protection is the use of direct methods (e.g., wind machines, heaters, over-vine sprinklers), applied just before or during frost events.

The most important strategic responses to late spring frosts are passive methods, namely site selection and choice of grapevine variety. Winegrowers need to avoid planting vineyards in frost-prone areas (e.g., low-lying) or select late-ripening varieties for those areas (e.g., Cabernet Sauvignon).

As the incidence of late-spring frosts is also highly variable over time, winegrowers may take risks in planting vineyards in frost-prone areas. To that end, fuel heaters in vineyards and a wind machine are necessary. During radiation frost conditions, wind machines mix warmer air aloft with colder air nearest to the soil surface, consequently increasing the air temperature around vines. The absence of these active protection methods may be costly (installation and operation) because of vineyards geographically spread out.

MEDIUM TERM ADAPTATION OPTIONS

CHOICE OF ROOTSTOCKS AND CLONES

In the medium term, adaptation to climate change will lead to changes in perennial practices.

- A first adaptation possibility concerns clonal selection. For most of the major grape varieties grown, there are currently 8 to 10 day maturity differences between clones of the same grape variety. This natural variability can be exploited rapidly during new plantings, so as to shift the production cycle in order to delay maturity and avoid harvesting in periods too hot. The interest is to be able to graft grape varieties with later clones of these same grape varieties.

- A second level of adaptation concerns the choice of the rootstock. This makes it possible to adapt to the physical and hydric properties of the soil; it will condition the functioning of the vine in terms of precocity, water supply regime and vigour. It is complementary to the choice of planting site. The choice of plant material is a major tool to adapt vineyards to greater water deficits. Rootstock resistance to water deficits is highly variable. The genetic basis of these differences is currently under investigation. Some existing rootstocks, like 140 Ruggeri or 110 Richter, are highly resistant to drought. One of the priorities of today's viticultural research is to create new rootstocks that show even greater drought resistance. The great advantage of adapting vineyards to increased drought stress through the choice of rootstock is that it is environmentally friendly and does not increase production costs.

MEDIUM TERM ADAPTATION OPTIONS

SITE SELECTION

Within a small territory there is many local topographical or soil situations that allow winegrowers to adapt to climate change. Indeed, differences in grapevine phenology as well as in grape and wine quality are often observed within short distances in a wine growing region and are related to local characteristics such as aspect and soil type.

- The spatial variability in climate at local scales and the analysis of these microclimates is a method of adaptation to climate change.

These local variations are crucial to assess the effect of climate change on viticulture, as the impacts will be region and variety dependant. It requires therefore to be investigated systematically in order to be considered in viticultural planning and management for improving adaptation to climate change. Topography, slope and aspect are factors that can allow the winegrower to adapt locally to climate change. The seasonal temperatures at the top of the hillside be several degrees different than at the bottom of hillside. The winegrower may modify his cultivation practices according to this temperature variability.

It is the same depending on the soil texture and depth. With increasing drought, deeper soils with higher soil water supply will be preferred. The deepest and most water-resistant soils should be reserved for those vines most sensitive to water stress, while more resistant varieties could migrate to drier soils.

LONG TERM ADAPTATION OPTIONS

CHOICE OF GRAPE VARIETY

In the context of quality-oriented wine production characterized by a distinctive varietal or regional trait, the cultivated grape variety, and in particular its ripening period, must be adapted to the climatic conditions of the surrounding environment. To avoid quality alterations caused by high temperatures during fruit ripening, phenology should be delayed. Plant material is a major tool for reaching this goal.

- Winegrowers can use rootstocks that induce a longer cycle, and clonal selection should be oriented toward late-ripening clones. These adaptations will not change wine typicity, and together, they can delay ripeness by approximately seven to ten days.

However, over the long term, ripeness can be delayed much more by the use of late ripening varieties.

- Late-ripening varieties can be found among the traditional varieties in some wine-growing regions. However, it might be necessary to use non-local varieties. This adaptation is obviously difficult to implement in European wine growing regions with traditional appellations. In these appellations, winegrowers can only use local varieties. It might become important to start experimenting with a small proportion of non-local varieties, in order to have accumulated enough experience by the time a major change in varieties becomes unavoidable (Van Leewen and Darriet 2016).

LONG TERM ADAPTATION OPTIONS

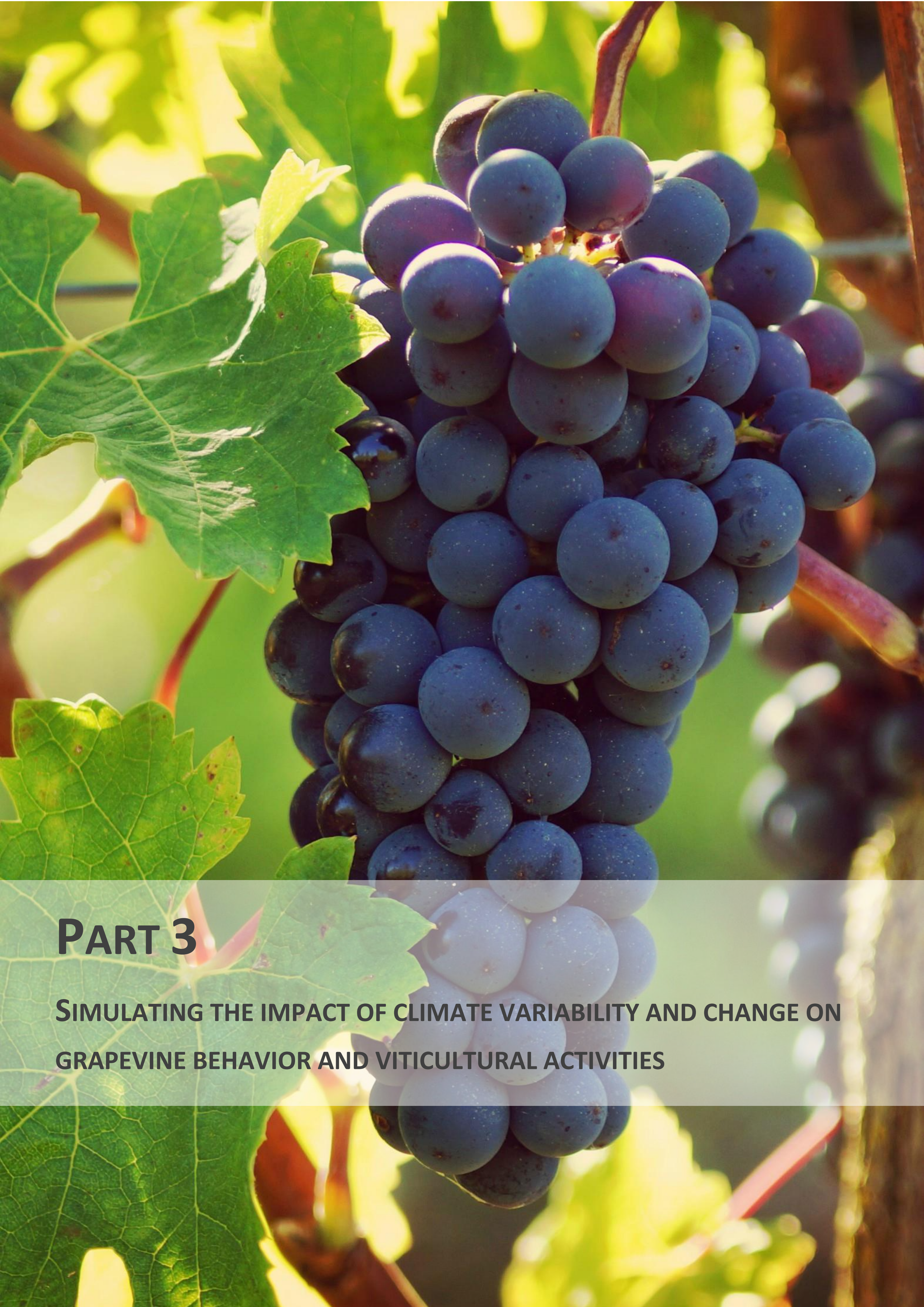
IRRIGATION

Irrigation is the process of applying extra water in the cultivation of grape vines. The amount of available water affects photosynthesis and hence growth, as well as the development of grape berries. While climate and humidity play important roles, a typical grape vine needs 250mm of water during the season, to avoid stress. A vine that does not receive the necessary amount of water will have its growth altered in a number of ways.

Several methods of irrigation can be used in viticulture depending on the amount of control and water management desired. Historically, surface irrigation was the most common means using the gravity of a slope to release a flood of water across the vineyard.

- Drip irrigation system provides the most control over water management, though expensive to install. With this system, a winegrower can control the precise amount of water that each grapevine gets down to the drop.

Unlike the other solutions proposed here, irrigation has an economic, environmental, and social cost. When water is becoming increasingly scarce, the irrigation of a drought-resistant plant such as vines should not be a priority. Moreover, irrigation can lead salt to build up in vineyard soils, when winter rain is insufficient for leaching it out of the soil. Vines are highly sensitive to salt, so its build-up can make soils unsuitable for grape production. When irrigation is the only option for maintaining vineyards in a given area, deficit irrigation should be implemented, both to save water and to optimize grape quality.



PART 3

SIMULATING THE IMPACT OF CLIMATE VARIABILITY AND CHANGE ON GRAPEVINE BEHAVIOR AND VITICULTURAL ACTIVITIES

Introduction

Within the context of a global changing climate, most studies that address future impacts and potential adaptation strategies are largely based on modelling technologies. However, very few studies model the complex interaction between environmental features, plant behaviour and farming activities at local scales. In viticulture, this level of assessment is of particular importance, as it is the scale where adaptation matters the most. The last part of this manual presents therefore the modelling framework used in the LIFE-ADVICLIM project to simulate the impact of climate variability and change on grapevine behaviour and viticultural activities. The modelling framework presented here is based on the prototype that was developed for the study area located in the Loire Valley, France.

VITICULTURAL PRACTICES

Grape and wine quality are much attributable to the unique characteristics of its geographical location, where winegrowers' decision-making play a key role. Prior to planting, decisions in terms of perennial practices are very important, e.g., selection of planting site, vineyard layout, choice in grapevine varieties. Thereafter, annual practices, e.g., soil, disease and canopy management, are constantly required to deal with multiple environmental and socio-economic issues. Figure 8 show the multifaceted and dynamic nature of decision-making in viticulture. Viticultural practices play therefore a central role in grape growing and wine production.

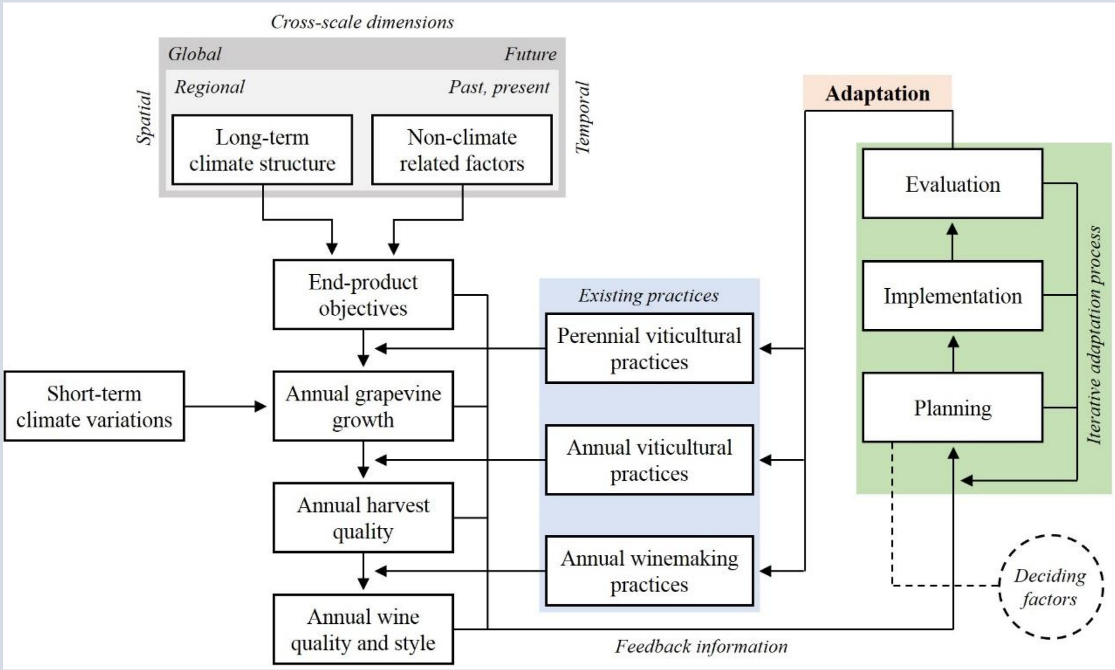


Figure 8: The multifaceted and dynamic nature of decision-making in viticulture (Neethling et al. 2016)

How to model grapevine behaviour and viticultural activities in the context of a changing climate?

The objective is to develop a generic modelling approach, able to simulate the dynamic and complex impacts of environmental conditions and constraints on grapevine behaviour and viticultural activities. For this, the project LIFE-ADVICLIM developed a model that has an agent-based simulation framework consisting of autonomous agents. As a result, three types of agents were designed:

- "Supervisor" Agents - imposes specific production regulations on winegrowers
- "Winegrower" Agents - grow grapes and produces wine
- "Vine" Agents - represent the vineyard plots

The behavioural relationship between these three types of agents determine the production strategies adopted by the "Winegrower" agents. The simulation framework of the model is broken down into four thematic groups. The first is focused on modelling the phenological cycle of the grapevine. The second includes specific elements related to the vineyard management structures. The third integrates all the climatic characteristics of the simulated vineyards. And lastly, the fourth thematic group is dedicated to the simulation of the grapevine pests and diseases.

MULTI-AGENT MODELLING

Multi-agent modelling is a technique for describing and simulating complex systems, which are characterised by interactive autonomous agents. In this context, agents are computing systems that occupy a complex and dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they were designed. For the assessment of viticultural systems, a multi-agent modelling framework is very appropriate as it responds to the need to formalize a coherent relationship between the spatial and temporal dynamics of grapevine behavior and winegrowers' activities in the context of current and future environmental processes, as well as with regards to technical, socio-economic and regulatory conditions and constraints.

Modelling the phenological cycle of the grapevine

In order to characterise the "Vine" agents, the multi-agent model mobilizes an important knowledge base informing all biophysical and agronomic parameters related to grapevine growth and performance. The "Vine" agents have therefore many attributes related to the specific characteristics of the production plots (e.g. in terms of elevation, aspect, soil texture...). During the simulation process, these agents will respond to temporal and spatial variations in environmental conditions and follow specific growth stages that are related to the annual vegetative and reproductive cycle of the grapevine phenology (Figure 9). They are also influenced by other disturbances, such as the frequency and intensity of fungal diseases. To achieve this, the annual growth dynamics of each "Vine" agent uses simple algorithms that are based on the principal of heat accumulation.

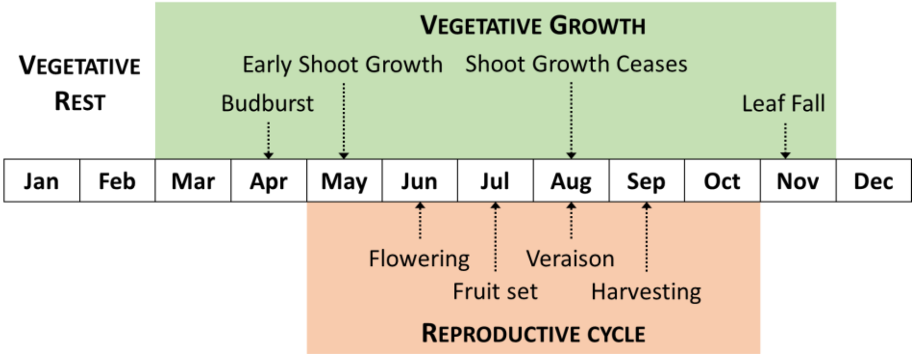


Figure 9: Annual vegetative and reproductive cycle of the grapevine in the northern hemisphere.

Vineyard management structures

To understand and integrate viticultural management practices and decision making at plot- to farm-level, in-depth surveys were first carried out. The aim was to produce a detailed description of management practices by placing them in the context of current and potential future environmental conditions.

- Firstly, winegrowers were interviewed in order to evaluate the sensitivity of 21 viticultural annual practices to climate conditions. Winegrowers were asked to describe working periods, techniques and machinery involved, and importantly to define environmental variables that determine favourable and unfavourable working days.

- Secondly, winegrowers were interviewed to evaluate their perception, vulnerability and adaptation to climate variability and change. For this survey, winegrowers were asked to describe general information related to their farm structure, trends in cultural practices and causing factors for these changes over the past few decades. They were also asked to define the environmental conditions that are favourable and unfavourable for grapevine behaviour and wine quality and the adaptation strategies employed to manage those conditions (Table 2).

Lastly, they were asked to describe their perceptions of past and future climate changes and notably the potential adaptation strategies necessary at short- to long-term. A classification of winegrowers was realized from the surveys. This allowed understanding winegrower's plot-to farm-level organization and production strategies, as well as environmental conditions and constraints in implementing vineyard management practices. Unlike many classifications that are based on size and other technical criteria, this classification used a functional criteria (business structure…) together with wine growers' perceptions of climate variability and change (level of sensitivity, reaction time, etc.).

Table 2: Types of adaptive responses used by winegrowers to manage climate conditions.

Adaptive responses	Climatic stimuli	Examples of viticultural practices
Tactical, reactive	Cool, wet	More severe leaf, shoot, crop thinning
	Warm, dry	Less severe leaf, shoot thinning Foliar nitrogen fertilization
	Wet ripening period	Several harvests via bunch selection Harvesting at night by machine
	Frost	Requesting crop insurance Turning on heaters/wind machines
Tactical, anticipatory	Cool, wet	Advancing canopy management practices Allowing natural vegetation to grow Higher number of fungicide treatments
	Warm, dry	Delaying canopy management practices Shallow soil tillage
	Frost	Delaying winter pruning Mowing cover crops
Strategic, reactive	Cool, wet	Longer cane pruning
	Warm, dry	Changing perennial cover crop species Increasing the trellis system height
Strategic, anticipatory	Cool, wet	Site selection
	Drought	Choice of rootstock variety
	Frost	Site selection, choice of grapevine variety

Integrating climate data

Daily data related to temperature, rainfall, solar radiation, wind speed and direction were provided by a network of weather stations and temperature sensors located in the vineyards. They were used to calculate all relevant bioclimatic indices permitting to simulate grapevine growth and performance. Therefore, temporal and spatial climate variability has a direct impact and in real-time on grapevine growing dynamics of “Vine” agents and “Winegrower” agent activities. In this context, both past and predicted weather data (i.e. with a 4 day window) are provided to “Winegrower” agents in order to establish a forecasting strategy. The integration of long-term climate change scenarios (according to the fifth assessment report of the Intergovernmental Panel on Climate Change, IPCC) is much more complex. This difficulty is due to the output scale of the regional climate models. As a result, simulation outputs are generally too broad to be applied. Indeed, to take into account the impact of climate variability on grapevine behaviour and viticultural activities, the model requires small scale data such as temperature, rainfall and potential evapotranspiration. To work around this limitation, climate data are integrated at a two scale level. At the most aggregated level that is managed by the model (meso scale), regional grids are used to simulate the impact of climate change on agroclimatic patterns. At the micro-scale level, the model integrate downscaling outputs (Figure 10).

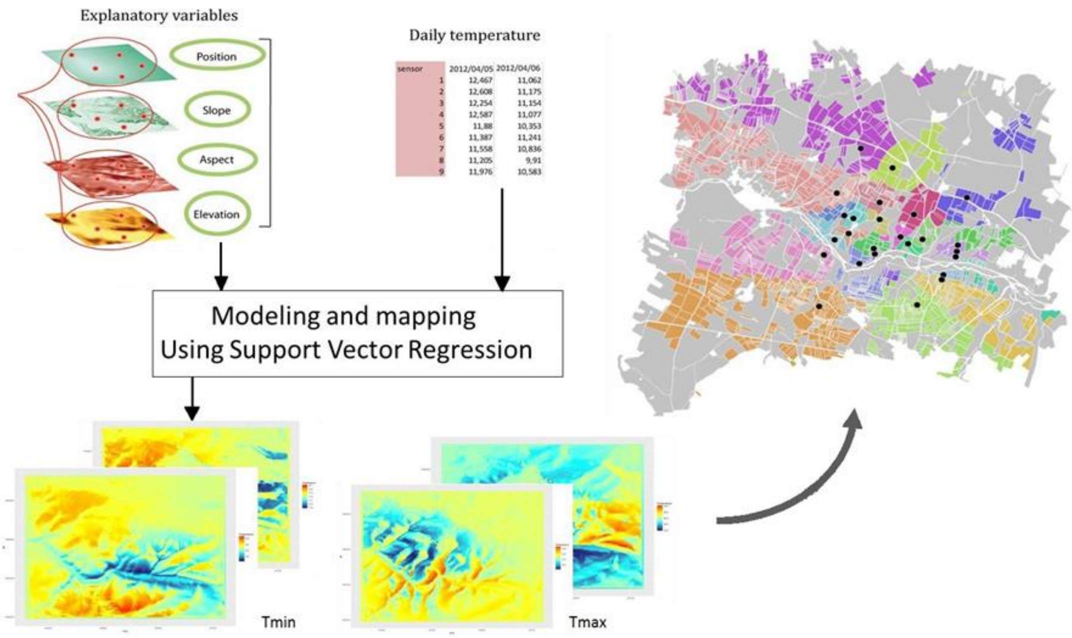


Figure 10: Integration of temperature data at high resolution level. Example of the AOP Coteaux du Layon (located in the Loire Valley, France).

Modelling viticultural practices in actual climate conditions

As mentioned before, the aim of these simulations are to relate grapevine behaviour with climate variability and viticultural activities in the context of a changing change. To achieve this goal, first simulation tests were dedicated to the Loire Valley, France, in order to assess the capacity of winegrowers to adapt to the rise in temperatures and the change in rainfall in order to produce sweet white wines. In this context, simulated viticultural practices will depend on grapevine phenological stages, environmental conditions and constraints as well as winegrower's production strategies (i.e. conventional, integrated or organic farming). Therefore, winegrower management practices are simulated according to three production profiles: conventional (i.e. traditional viticulture), integrated (i.e. limitation of pesticides, fertilizers and weeding) and organic farming (e.g. strong limitation of pesticides, use of mechanical weeding...). According to their production profile and vineyard agro-climatic characteristics (e.g. topography, soil water balance), each “Winegrower” agent performs a specific agronomic action. The decision making process allow to determine and evaluate an agronomic itinerary for each vineyard plot according to the annual climatic profile and the winegrower’s production strategies and objectives (Figure 11).

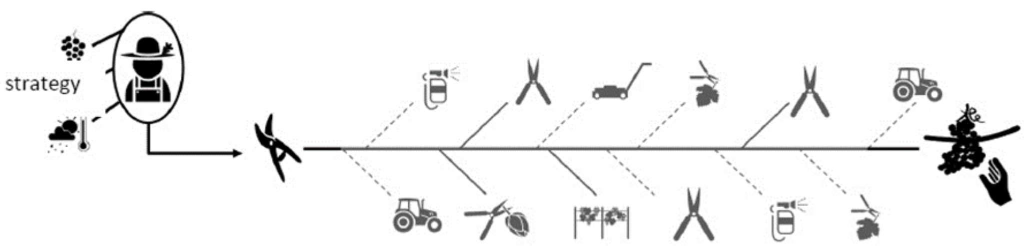


Figure 11: Simplified agronomic itinerary simulation for one “Winegrower” agent

The agronomic itinerary can integrate general agronomic actions (e.g. winter pruning, shoot trimming, leaf thinning...) but also adaptation responses to specific climate constraints (e.g. soil and pest management). Therefore, the choice of an agronomic action or an adaptation measure is not only determined by the seasonal grapevine behaviour or climate variability, but it is also strongly dependent on production strategies and objectives, which vary among winegrowers based on their business structures (e.g. family owned or private, farm size, etc.), and their sensitivity to climate conditions (e.g. threshold values depend on winegrower's production profile). Retrospective simulations conducted in the growing seasons of 2003 (hot and relatively dry), 2005 (warm and dry), 2007 (wet and relatively cool), 2011 (warm and dry spring) and 2013 (wet and cool) shows an important variability in the grapevine vegetative and reproductive cycle, depending on the climatic profile of each year (Figure 12).

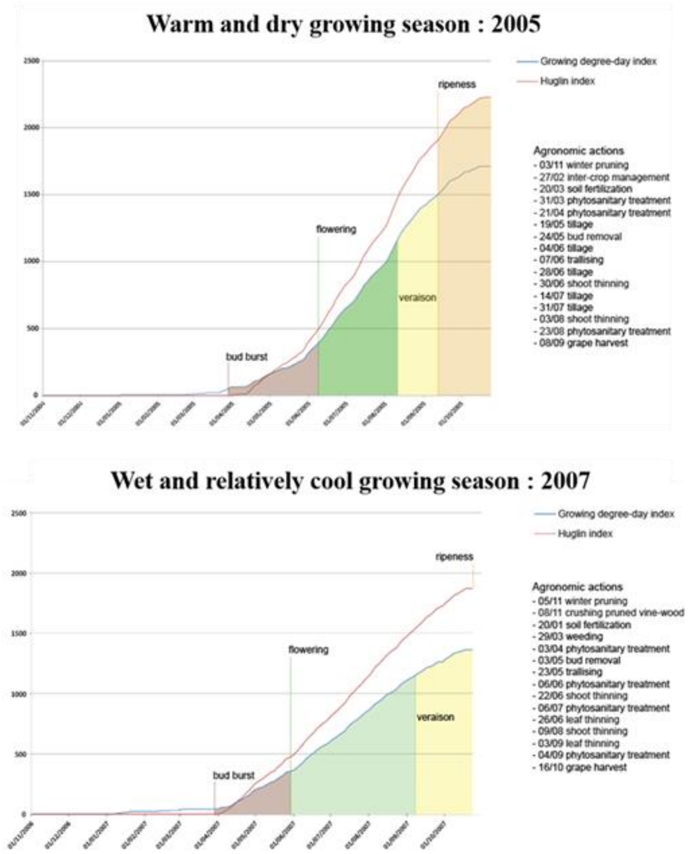


Figure 12: Simulation results for two years with different climatic profiles.

Climate variability directly affects agronomic practices, which can be more or less numerous, both over time and space. In hot and dry climate contexts, shallow soil tillage activities will be used to limit grapevine water stress, especially in vineyard plots with low water holding capacities. In normal to wet growing seasons, inter-cropping management practices will be used to manage grapevine vigor and yield, especially in deep soils with high water holding capacities. The use of pesticides is less correlated to the global profile of the growing season, as it depends on the season distribution of temperatures, humidity and especially rainfall (i.e. both amount and intensity). If these elements are highly correlated with grapevine phenological properties, winegrower's individual strategies can completely change the choice of an action or a specific tool. For example the use of pesticides can vary depending on the production profile. In organic production, the use of contact products requires a high spray frequency during periods of an increased risks of pathogenic diseases and frequent rainfall (a few days between each spay). In conventional production, by using systemic product, wine growers reduce significantly this frequency (usually 14 days between spraying). The priority level of this action is variable depending on winegrower's profile. The multi-agent model allows bringing out specific behaviors and assessing the impact of its behavior on the emergence of new adaptation practices.

Modelling viticultural practices in future climate conditions

The second step was to integrate the regionalized scenarios of climate change. Accordingly in the meso-scale model, several prospective assessments were undertaken in the Loire Valley pilot site, by integrating the regional climate projections of three Representative Concentration Pathways (i.e. RCP 2.6, 4.5 and 8.5) which describe possible climate futures according to their greenhouse gas concentration trajectories. Depending on the chosen climate scenario, the results show an important temporal variability and shift in the grapevine phenological cycle (Figure 13). These results are representative of the increase in seasonal temperatures that will significantly affect the timing of grapevine earliness and the ripeness level of grapes. However, for the RCP 8.5, the grape harvest action is not correlated to this shift in grapevine phenology, because it depends also on the choice of winegrowers to harvest or not. According to their perception of climate conditions and particularly the type of wine they would like to produce, winegrowers will manage harvest dates.

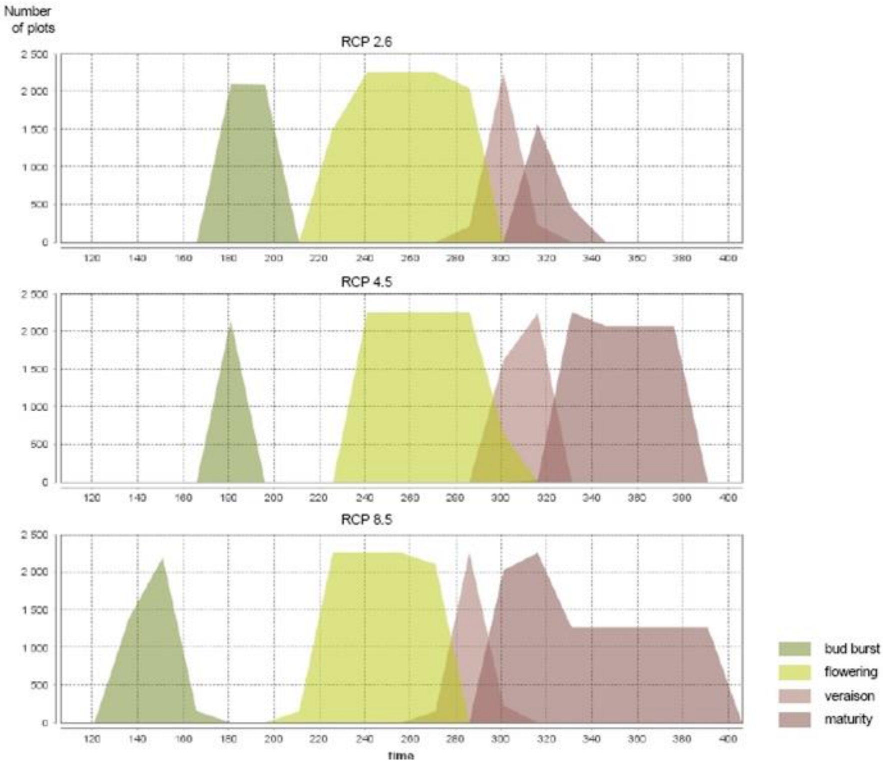


Figure 13: Simulation result for the year 2060 at meso-scale level. For year 2060, there are some significant differences between the three RCP's. The duration of each phenological stage, highlighted by a specific colour, varies greatly. This variability is correlated to the increase in temperatures that affects vine earliness and grape ripeness level at harvest.

At the meso-scale, the simulations can also integrate the physical characteristics of vineyard plots as well as the agronomic actions carried out, depending on the climate scenarios. However, despite a strong increase in temperatures over the next century, the results show that the inter-annual variability in climate conditions remain an important deciding factor of decision making.

These results show that with a changing climate, the risk is that annual or daily climate variability may overshadow local winegrowers' perceptions of long term temperature and rainfall changes. That means future uncertainties for winegrowers, as they attempt to minimize annual variation in grape yield and quality, by adapting optimally their annual and especially perennial practices. The risk is that future adaptations in perennial practices will likely be limited by climate variability that will oblige wine growers to intensify even more their present soil management and canopy management practices. Within this perspective, these results indicate the need to find a coherent relationship between the outputs of the meso- and micro-scale multi-agent model that is used in action B1. Indeed, by coupling these multi-scale analysis, modelling findings should seek to provide more clear guidelines on planning and adapting to uncertain long term climate changes, which is a major challenge for the wine industry.

Perspectives

The modelling approach presented in this third part addresses the impact of environmental conditions and constraints on grapevine behaviour and the dynamics of viticultural activities. Through the development of this modelling approach, the impact of climate variability on grapevine performance and winegrowers' production strategies was specifically targeted, both over time and space. Methodologically, realized developments have contributed to formalize relationships between a network of reactive agents and a constrained environment. The coupling between spatio-temporal data and this multi-agent modelling framework is in this perspective a relevant way to improve the integration of heterogeneous constraints to suit the variability of grapevine behaviour and winegrowers' end-product objectives.

The first results show that the developed multi-agent model is able to reproduce the behavioural dynamics of grape growing and viticultural practices according to climate variability. In the context of climate change, such a dynamic and complex model will help to better assess potential impacts on viticulture and to frame adaptation solutions at different temporal and spatial scales. Many perspectives are still considered. They are mainly focused on improvements for assessing various adaptation measures on grapevine growth and grape quality. Technically, this means introducing feedback loops in the model in order to simulate the implications of viticultural practices on the grapevine (level of vigour, vine earliness, resistance to pathogens, etc.). The integration of other indicators including measuring the potential quality of grapes at harvest is also considered. Exchanges with local winegrowers are likewise essential to validate and improve the model, but also to build relevant scenarios for climate change adaptation. In this context, work sessions are planned to collectively define experimental and prospective simulations. These further developments are considered for the different vineyard study areas that are part of the LIFE ADVICLIM project, namely in Romania, Germany, United Kingdom and France.

For more information on climate change adaptation in viticulture, please read:

- Tissot C., Neethling E., Rouan M., Gérard B., Quenol H., Le Coq C., 2017. Modelling environmental impacts on viticultural ecosystems: A first case study in a regulated wine producing area, International Journal of Agricultural and Environmental Information Systems, in press.

- Neethling, E., Petitjean, T., Quénol, H., & Barbeau, G. (2016). Assessing local climate vulnerability and winegrowers' adaptive processes in the context of climate change. Mitigation and Adaptation Strategies for Global Change, Springer Verlag, 1-27. doi:10.1007/s11027-015-9698-0

- Tissot C., Rouan M., Neethling E., Quenol H., Brosset D., 2014. Modeling of vine agronomic practices in the context of climate change, BIO Web of Conferences 3, 01015 (2014), EDP Sciences, DOI: 10.1051/bioconf/20140301015.

CONCLUSION

According to the latest climate projections published by the IPCC in 2013, current climate change will continue and intensify in the future. Continued warming in the 21st century is expected to lead to significant advances in phenological stages, as has been observed in recent decades. This very probable advance of the phenology of the grapevine raises many questions: in the short term, it is likely to have important consequences on grape composition; the latter being linked to higher temperatures and an earlier maturity period, where the grapes ripen in warmer conditions. The future change of grape quality inevitably means changes in the quality and style of produced wines. Although the adaptation of annual practices is already underway, wine growers must rethink their practices and strategies in the medium and long term in order to respond to the expected effects of climate changes.

To that end, several adjustments can be made. In the short term, adaptations can be made in terms of harvest, soil and vigour management practices. While in the medium to long term, changes should be made in the choice of rootstock varieties, and eventually, in choosing new grapevine varieties or expanding viticulture to non-traditional planting sites. However, adaptation to climate change needs to be considered at different spatial and temporal scales in relation to a better understanding of the characteristics of the local environment. Factors such as topography and the nature of the soil have important effects on the local variability of the climate and the behaviour of the grapevine, and consequently on the quality and the typicity of the wine.

CLIMATE CHANGE MITIGATION

While this manual only deals with climate change adaptation, it is necessary to develop viticultural strategies that promote both sustainable wine production (i.e. in terms of quality and quantity) and reduction in greenhouse gas emissions. The B2 action of the LIFE-ADVICLIM project deals with these related issues in viticulture. The objective of this project is therefore to find synergies between adaptation and mitigation measures to climate change.

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http://www.adviclim.eu/