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IMPACT OF CLIMATE CHANGE ON VITIS VINIFERA L. OVER MEDITERRANEAN AREA

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"Share your knowledge.
It is a way to achieve immortality"

Dalai Lama

SUMMARY

Abstract

Several agricultural sector are likely to be sensitive to climate change conditions. Vitis vinifera L. is particularly sensitive to climate change because of the linkage between climate variability, phenology and characteristics of the resulting product. This thesis discusses an investigation conducted at different scales in order to analyse the effects of climate change on VitisVinifera L. in the Mediterranean basin.

At the European scale a methodology to study the vocationality area under climate change conditions was developed using three bioclimatic indicators (Huglin Index, Cool Night Index and Dryness Index) and soil characteristics (slope and depth). At the national scale (Italy), an evaluation of the impact on twelve different wine grapes varieties under climate change conditions (RCP 4.5 and RCP 8.5) has been undertaken. In order to study the annual growth cycle of grapes, six different phenological models, developed in the Phenological Modeling Platform 5.5, have been compared.

At the regional scale (Sardinia), how the impact of climate change might modify the yield rate has been described using a crop-model (STICS) on a new parametrised cultivar (Cannonau) and three other varieties (Cabernet Franc, Merlot and Syrah) reason of interest for vitivinicultural Sardinian reality.

Generally, the results of the impact of climate change on grape cultivation showed a northern shift of the suitability area, a shortening of the growth cycle to the detriment of developmental stages, while yield remains more or less constant.

Chapter 1: Introduction

Climate change

"*Climate change in IPCC usage refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.*"

With these words the IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report (AR4): Climate Change 2007 defines climate change, and in the latest IPCC report (AR5) these sentences were unequivocally sustained.
According to van der Linden et al. (2015), the scientific consensus on human-caused climate change is observed in several studies, including analyses of specialists and complete reviews of the peer-reviewed literature on climate change. All these approaches reveals that no less than 97% of climate scientists have established the anthropogenic responsibility of climate change (Cook et al., 2013).

The IPCC 2014 Report, in fact, assumes the likelihood of human activity being responsible for:

- Increase in global average surface temperature and global mean surface warming of 0.6°C up to 0.7°C, from 1951 to 2010, due to both the rise of anthropogenic greenhouse gas (GHG) concentrations and other anthropogenic forcing. (Fig.1.1)

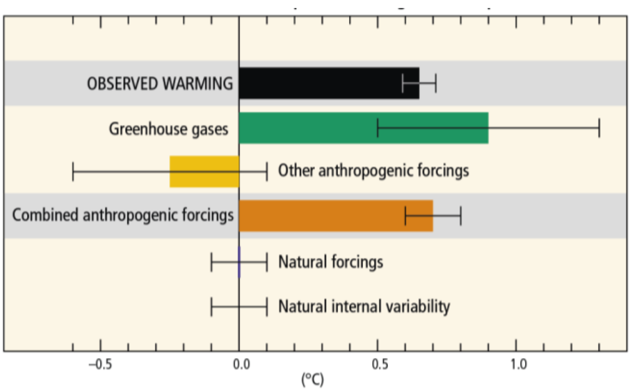


Figure1.1: Contributions to observed surface temperature change over the period 1951-2010 (AR5)

- Cooling in the lower stratosphere since 1961 as an effect of the tropospheric warming led by GHGs and stratospheric ozone depletion
- *Contributing to* "Arctic sea ice loss since 1979"
- "Contribution to the retreat of glaciers since the 1960s and to the increased surface melting of the Greenland ice sheet since 1993. It is likely that there has been an anthropogenic contribution to observed reductions in Northern Hemisphere spring snow cover since 1970."
- *Modifying the global water cycle since 1960, in terms of increase* "in atmospheric moisture content […], global-scale changes in precipitation patterns over land […], intensification of heavy precipitation over land regions […],and changes in surface and subsurface ocean salinity."
- "Contribution to increases in global upper ocean heat content (0–700 m) observed since the 1970s, […]", *influence on* "thermal expansion and glacier mass loss" *also* due to the "oceanic uptake of anthropogenic CO2."

In summary in the last decades, changes in climate have produced effects on natural and human systems over land and the oceans. These changes have entailed and will continue to involve extreme events in climate condition, in terms of decrease of cold days and nights and increase of warm days and night numbers, as well as the increase of heat waves in Europe, Asia and

Australia. At a global scale, a modification in daily temperature extremes intensity and frequency as well as heavy precipitation events were observed, thus implying the possibility of flooding risks at regional scale.

Then, it is understandable how heat waves, droughts, floods, cyclones and wildfires, influence the vulnerability of eco and human systems to climate variability. (Fig.1.2)

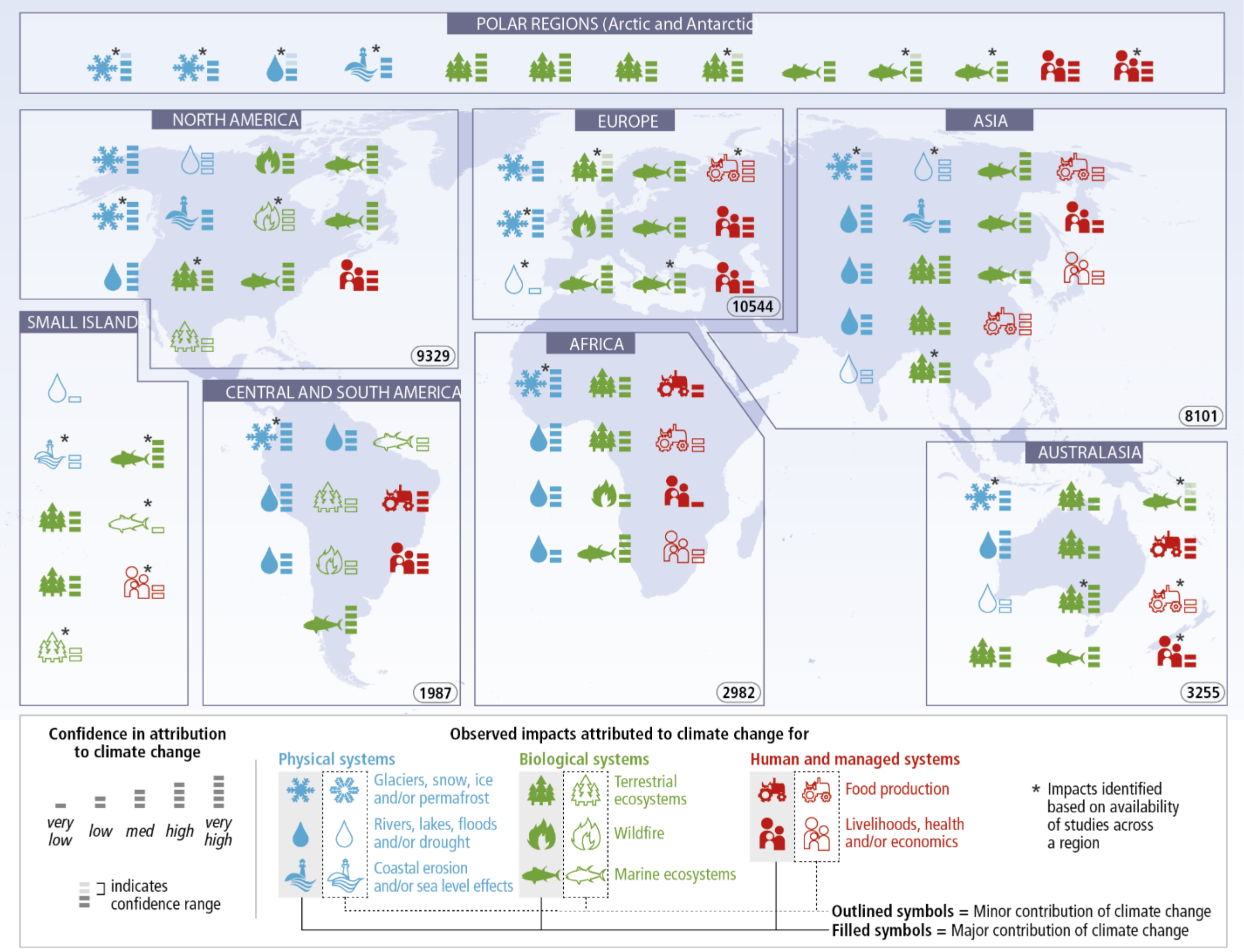


Figure 1.2: Widespread impacts in a changing world based on the available scientific literature since the IPCC AR4. Symbols, grouping at regional-scale affects, indicate impacts attribute categories in relation to the contribution of climate change (major or minor) and the level of confidence in attribution. In each region, the numbers in ovals indicate the publications from 2001 to 2010, based on the Scopus bibliographic database for publications in English with individual countries mentioned in title, abstract or key words (as of July 2011)(AR5).

To contain climate change and to limit associated risks, it is necessary to get to considerable and continued reductions in greenhouse gas emissions by implementing adaptation and mitigation strategies.

Different projection were developed to describe four different Representative Concentration Pathways (RCPs) of GHG emissions of 21st century scenarios(Van Vuuren, et al., 2011) (Fig.1.3):

- RCP 2.6, a severe mitigation scenario pathway where radiative forcing peaks at approximately 3 W/m^2(~ 490 ppm CO_2eq) before 2100 and then declines (Van Vuuren, et al., 2007; Van Vuuren, et al., 2006);
- RCP 4.5, first intermediate scenario pathway in which radiative forcing is stabilized at approximately 4.5 W/m^2(~ 650 ppm CO_2eq) after 2100(Clarke, et al., 2007; Smith & Wigley, 2006; Wise, et al., 2009);
- RCP 6.0, second intermediate scenario pathway in which radiative forcing is stabilized at approximately 6.0 W/m^2(~ 850 ppm CO_2eq) after 2100 (Fujino, et al., 2006; Hijioka, et al., 2008);
- RCP 8.5, scenario with very high GHG emissions level for which radiative forcing reaches >8.5 W/m2 (~ 1370 ppm CO2eq) by 2100 and continues to rise for some amount of time (Riahi, et al., 2007).

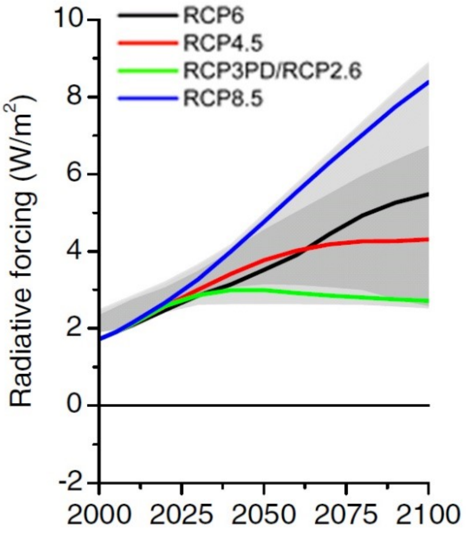


Figure 1.3: RCPs scenarios (Van Vuuren, et al., 2011)

According to these RCPs, different changes in the climate system may be forecast.

At the end of the 21st century, the global mean surface and air temperature will likely increase, precipitations will be variable in altered rate at different latitudes; there could be oceans warming and acidification, and a decrease of the global glacier volume. To reduce and manage the risks described above two complementary strategies were developed in order to adapt and mitigate climate alteration. Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. The first is a sort of regulation to actual and simulated climate condition effects in order to take advantages of beneficial opportunities and, at the same time, reduce or avoid harms. The second is an approach aimed at limiting the impacts of future climate change, reducing the emissions or enhancing sinks of greenhouse gases (GHGs).

However, adaptation and mitigation can generate different risks in consequence of the modification of the systems, in terms of rate and magnitude of the change hypothesized and in relation to the vulnerability and exposition of anthropic and natural systems.

For that reason, different factors are considered in the choice about adaptation and mitigation strategies, not least ethical and societal aspects (IPCC, 2014).

Climate change in agriculture

In AR5, the Agricultural sector is consider together with the other terrestrial land surface sectors, namely Forestry and Other Land Use, with the acronym AFOLU. Thanks to that, Land became the principal actor of the AFOLU sector. In the AFOLU chapter of AR5 (Smith, et al., 2014) different important functions of land are underlined, such as the food and fodder to feed the Earth's population supply, in addition to providing fibre and fuel for different purposes. It is also important to remember that land is a finite resource that provides livelihoods, goods and ecosystem services for people worldwide. Several ecosystem services, goods and benefits provided by land are linked as show in Figure 1.4.

According to Wreford et al. (2010), agriculture is a "man-made adjunct to natural ecosystems" dependent on weather and climate factors.

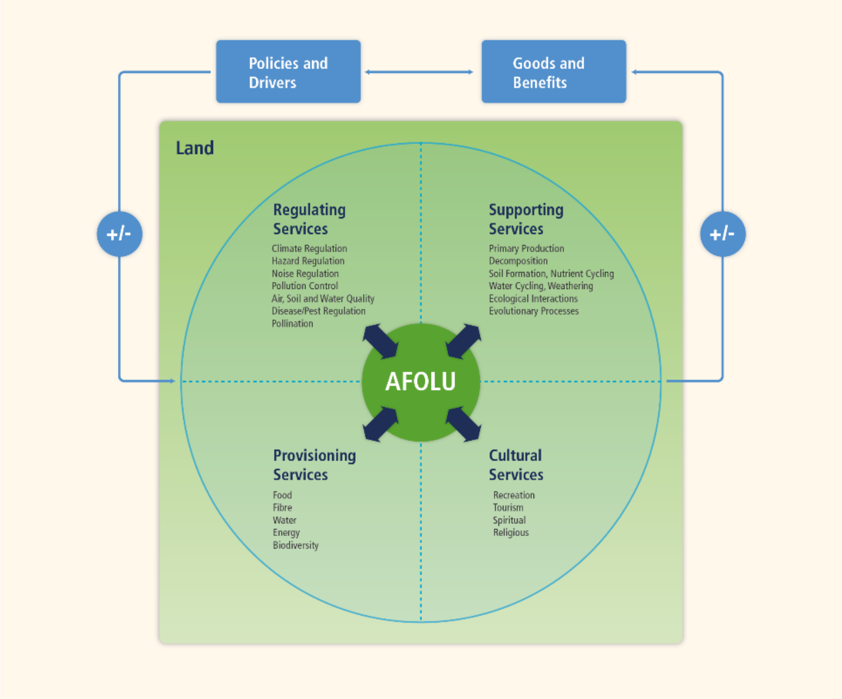


Figure 1.3: Multiple ecosystem services, goods and benefits provided by land (Smith, et al., 2014)

Over the last 20 years, knowledge about climate change impacts on agriculture have increased. Convergent results show that global food production will be altered by climate change. Negative impacts on crop productivity are anticipated in low latitude and tropical regions, whereas rather positive ones are expected in high-latitude regions. (FAO, 2015)

As an example, Mirza (2011) focused on floods occurrence in South Asia. In Bangladesh, India and Pakistan, in fact, the extreme floods frequency is actually rising, but magnitude and extent flooding may, also, increase in future due to climate change. The increases in future flooding will have consequences on extensive rice crops due to the monsoons. These effects may likely have implications on food security and, as a consequence, impacts on public health in coastal areas and flood plains.

At farm level, Anwar et al. (2013) proposed a review of different adaptation strategies. Among other concepts, summarize the implications on the productivity in agricultural sector according to the different climate components as shown in table below (Tab.1.1).

Table 1.1 Components of climate change: implications on farm-level agricultural system productivity (FASP). Anwar et al.(2013)

Components affecting agricultural farming system	***Implications and concern***	***Observed and projected changes***
1. Climate variability due to Madden–Julian oscillation	Influence daily precipitation patterns, crop damages, soil degradation, and runoff	Observed recent changes (not necessarily due to anthropogenic climate change)
Quasi-biennial oscillation	Drought and cyclone, fluctuation of surface solar radiation and temperatures, precipitation variability, crop yield loss	
Southern annular mode	Precipitation variability, crop loss, coasta region production loss	
Indian ocean dipole	Bush fire, drought, crop loss	
ENSO and interdecadal Pacific oscillation	Precipitation variability, crop yield loss, drought and flood, vegetation loss, and soil erosion	
North Atlantic oscillation	Precipitation variability, drought and flood, land degradation, lower yields/crop damage and failure, livestock deaths	
2. Atmospheric CO2	Increase biomass in crops and weeds with non-limiting nutrient supply, weeds competition with crops, increase physiological water use; alteration in soil C/N ratio, in turn, modify hydrological balance, altered N cycle, increase in pathogens and diseases from greater fungal spore production, damage from insect, crop yield decrease	Increase
3. Temperature	Changes in crop physiological processes and metabolism, in turn, modification in crop suitability, productivity and quality; affects evapotranspiration, in turn, modify WUE; changes in weeds, crop pest and diseases; change in irrigation need	Increase
4. Heat stress	Grain yield reduction associated with pollen sterility, increase pollination failures, increase in pests, reduced productivity including reproductive success of livestock, decease fodder quality	Increase
5. Frost	Influences early and late frost events, in turn, inhibit and damage crops and pasture, changes in frequency	Increase/decrease
6. Precipitation	Increase year-to-year variability, in turn, productivity fluctuation and agricultural loss, increased precipitation intensity, changes in precipitation distribution, increase dryland salinization, soil erosion and runoff	Increase/decrease

7. Extreme events	Droughts, in turn, pressure on water supply, bush fires, floods affect water quality and exacerbate many forms of water pollution, soil erosion and runoff, crop and livestock loss	Increase
8. Atmospheric ozone O3	Productivity loss in crop and pasture, decrease quality of agricultural produces, lower soil carbon formation rate	Increase
9. Sea-level rise	Increase intrusion of seawater into estuaries and aquifers, impede drainage and soil quality, increase water salinization, crop damage	Increase

At European scale, different researches were conducted to evaluate the impact of climate change on agricultural systems, underlying the vulnerability of crops under water stress, heat stress or a combination of both conditions. Maracchi et al. (2005) and Olesen & Bindi (2002) studying the climate variability on agriculture and forestry in Europe, hypothesized an increase of agricultural and forestry productivity due to the increase of CO_2 concentration and, for that reason, an increase of water use efficiency. The effects of climate change will be different in various parts throughout north and south Europe.

Many regional variations on crop cultivation and crop productivity are expected in Europe by 2050. The impact will be both positive and negative in northern Europe as well as in the Mediterranean regions; the rate of such impact will depend on the possibilities to adopt different adaptation strategies so as to maintain current yields. The most negative effects will likely be in the Pannonian zone, in Hungary, Serbia, Bulgaria and Romania regions. There is a high probability that incidents of heat waves and droughts will increase, however it will not possible to shift crop cultivation to other seasons (Olesen, et al., 2011).

Adaptation strategies to reduce negative effects and advantage possible positive effects of climate change like adjusting (e.g. changes in crop species, cultivars and sowing dates) and planned adaptations (e.g. land allocation and farming system) should be considered (Bindi & Olesen, 2011).

Concerning the adaptation strategies, again, in Iglesias et al. (2012a, 2012b) was gave an interesting overview about the potential implications of climate change and adaptation choices for European agriculture in order to reduce the vulnerability of such sector.

According to FAO “Agriculture is a source of climate change but also a solution to climate change if adequate sustainable production measures are adopted that hold substantial mitigation potential, and that contribute to adapt agriculture and food production systems to extreme events, raising temperatures, and increasing CO2 concentration.”

Many strategies that are being proposed focus on net emissions reductions thanks to the farming practices aiming to the terrestrial bio-sequestration, the reduction of the application of inorganic fertilizer, the prevention of deforestation or the increase of afforestation and, at the same time, replacing fossil fuel energy with biomass and biofuel crops (FAO, 2015).

Climate change in viticulture

The capability of the grape to grow in a wide range of climates and environments is intrinsic in its genetic characteristics, and was emphasized thanks to the different management practices through a long historical evolution. (AA.VV., 2008)
Thanks to warm and cool periods of the past, the climates confines for the viticulture were conventionally positioned between 30°and 50°N and 30° and 40°S of latitude, geographically situated in the Mediterranean climates around the World corresponding to the isotherms ranging from 12° to 22°C for the period of the growth season (April–October, October–April) (Schultz & Jones, 2010) (Fig.1.5).

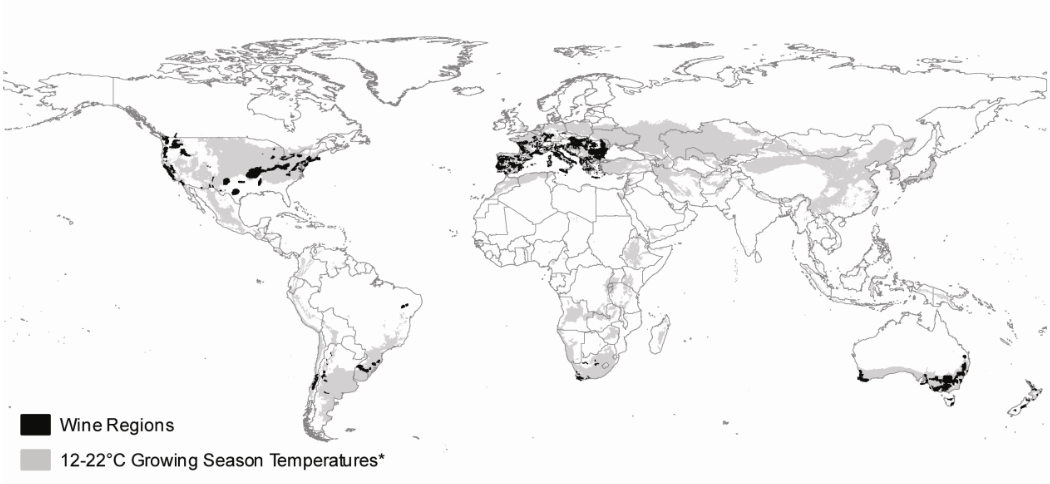


Figure 1.5: Global wine regions according to Schultz & Jones, 2010

According to the 38th World Congress of Vine and Wine (2015), 7573 thousands of hectares (mha) is the global area under vines in 2014 subdivided in 54% in Europe, 24% in Asia, 14% in America,5% in Africa and the 3% in Oceania. More in details, only five country covered 50% of the worldwide vineyard area, Spain with 14%, China with 11%, France with 10%, Italy

9% and Turkey with 7% (Fig.1.6).In the last fifteen years these rate were decreasing in Europe and, at the same time, were increasing in Asia, USA and in some areas of the southern hemisphere as Argentina and Brazil.

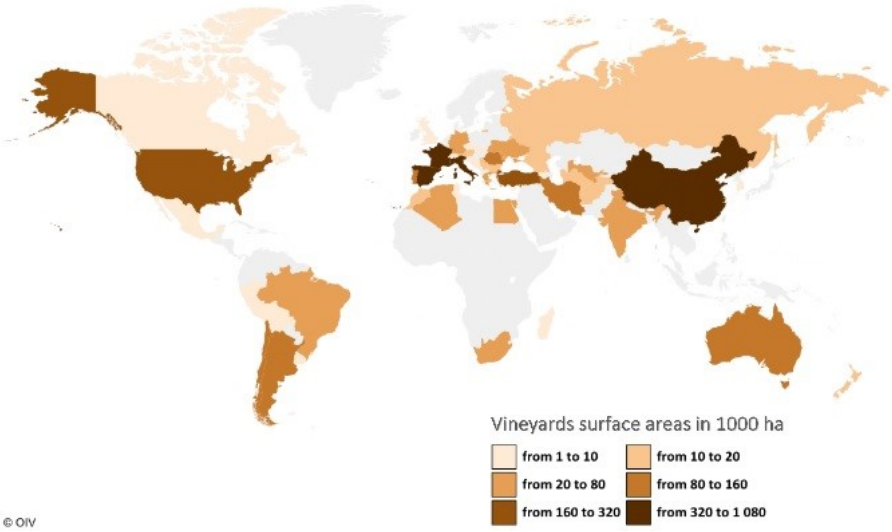


Figure1.6: Global surface areas of vineyard (OIV,2015)

Nevertheless, the production of grape has been increasing from 648 million of quintals (Mqx) in 2000 to 737 Mqx in 2014, 41% of which was produced in Europe, 29% in Asia and 21% in America.

This rise in production is due to an increase on yields, nevertheless it should be pointed out that the more favourable average temperatures due to the climate conditions contributed to the partial redistribution of the vineyard (OIV, 2015)

The wine-growing geographical limit described above were assumed in consequence of water and temperature limitations, and, thus, determined the original expansion of the vineyard in terms of the selection of local and wild varieties so as to identify the best areas to produce quality wines (Sotes, 2010). In order to protect and enhance the different vitivinicultural reality some particular definitions were developed, firstly by OIV in 1992 with "Recognised Geographical Indication (R.G.I.)" and "Recognised Appellation of Origin (R.A.O.)"and later, in 2008, the European Community coined two other expressions, namely “Protected Designation of Origin (PDO)” and “Protected Geographical Indication (PGI)”.These definitions underline the link between the importance of the use of geographical names and the national assets in the description of wines.

Another term that the OIV coined to identify a specific characteristic of a vitivinicultural system is "Terroir: a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied vitivinicultural practices develops, providing distinctive characteristics for the products originating from this area". In other words, the expression "Terroir" consists of "specific soil, topography, climate, landscape characteristics and biodiversity features".

Although there exist many aspects of "Terroir" that can affect the quality or viability of grapes, only few can relate to the effect of climate (temperature and hydrologic). Wine grapes, in particular, need some specific conditions to produce a characteristic flavour as well linked to climate during the years. The relationship between climate and wine suggests that grapevine cultivation can be an indicator of the impacts of future climate change. (Kubach, 2012)

Many studies were conducted to understand the impacts of climate change on grapevine and some hypotheses were assumed regarding adaptation and mitigation strategies.

In order to understand better the link between grape and climate, many researchers focused on the past effects of climate and the development of vineyard around the world. Chuine et al. (2004) used a French dataset of grape-harvest dates in the Burgundy area to reconstruct the spring-summer temperatures from 1370 to 2003, using a process-based phenology model settled for the grape of Pinot Noir. Similarly, Yiou et al. (2012) adopted the same methodology to obtain detailed information about the atmospheric circulation that were predominantly over the North Atlantic region during the Little Ice Age. Le Roy Ladurie et al. (2006) made an overview on the Burgundy climatic history, in the north of France, related to the grape harvest dates between XIV and XIX century. Garnier et al. (2011) too debated the relationship between temperature and the dates of grape harvest, in Besançon (French), across 1525 and 1847underlining the anthropogenic influences that have altered the date of harvest (i.e. military interventions and epidemics). Simultaneously, Wolfe et al. (2005), in the northeast of the USA, and Tomasi et al. (2011), in northeaster Italy, have observed a shift in grapevine phenology as a consequence of climate variability throughout the last fifty years.

Laget et al. (2008) observed, among others, some effects on viticulture in the Mediterranean areas of France, i.e. modification of oenological parameters, such as total acidity and sugar concentrations of grapes at harvest.

Given the close relationship between viticulture and climate, several authors wanted to analyse the effects that climate change will have on grapevine, reaching different conclusions in relation to the adopted scenarios.

Changes in grapevine phenology were observed at different levels, with an anticipation and a reduction in the growth cycle in Australia (Webb, et al., 2007), in France by Garcia de Cortázar Atauri (2006) and in Alsace by Duchêne & Schneider (2005), by Koufos et al. (2014) in Greece. Changing in the phenological timing was calculated also using different modelling approach. Parker et al. (2013, 2011) developed different methods to classify vegetative and reproductive development phases of grape, and according to that allow to combine these informations with the predicted climate change scenarios. Similarly Fila et al. (2014) studied the phenology of the Chardonay variety under present and future scenarios, in Veneto region (Italy).

A shift towards the most suitable area was analysed by Moriondo at al. (2013) , Fraga et al. (2013) and Santos, et al., (2012) at European scale, by Fraga, et al., (2015) in Portugal, by Kubach (2012) in Pensylvennia. Several authors have utilized the approach proposed by Tonietto & Carbonneau (2004) to improve the knowledge and identify the future adaptable vineyard regions (Fraga, et al., 2014; Irimia, et al., 2013; Tonietto, et al., 2010; Vuković, et al., 2010). Such method, also known as a Multicriteria Climatic Classification System (Géoviticulture MCC System), is very useful to characterize the worldwide grape-growing regions at actual climate conditions both in climate change scenarios.

Hannah, et al. (2013), that predict a decrease of suitable area from 25% to 73% in RCP 8.5 scenario conditions and from 19% to 62% in RCP 4.5 scenarios. At those observations van Leeuwen, et al., (2013) replied that the decrease of viticultural suitability would change with a lower rate.

Jones et al. (2005) outlined the changes in wine grape quality at global scale due to climate change predictions. Other results, according to the study area, were also observed by Santos, et al., 2011 for Porto wine in Portugal, by Kizildeniz et al. (2015), Ramos et al. (2015) and Parra, et al.(2010) for Tempranillo grapevine in Spain, on red wines in the Montsant DO in north-eastern Spain by Lopez – Bustins et al. (2014), and Webb, et al., (2008) in Australia.

According to that authors, in Palliotti et al. (2014) were reviewed the principal effects on grape ripening due to the climate change predictions.

In order to deal with the possible impacts of climate change on grape, some procedures were proposed, both in terms of adaptation and mitigation strategies. Malheiro et al. (2010) proposed different adaptation strategies, for example the change of grape varieties or the implementation of the irrigation. Lobell et al. (2006) suggested changes in oenological practices as a result of technological advances, while Bernetti et al. (2012) proposed a probabilistic approach, and provided an economic evaluation to assess the vulnerability of the vineyard systems and the effects that justify the adoption of some adaptation measures to preserve the identity and the quality viticulture.

As regards mitigation strategies, Soja et al. (2010) have shown that, to reduce the emissions of greenhouse gas, a reduction in the tillage intensity and the introduction of new packaging policy could be possible strategies.

Noteworthy is the LACCAVE project that studied the impacts of climate change on vitivinicultural system, and possible adaptation strategies for France. This work involved twenty-three research laboratories and expertise in different disciplines (climatology, genetics, ecophysiology, agronomy, oenology, economics, sociology...) in order to have a prospective approach in 2050.

Aims of the thesis

As shown in literature, many studies were conducted in relation to climate change and the vitiviniculture sector. The majority of these studies concern the European area, particularly the vitiviniculture regions of north Europe. Regarding the south, few studies were undertaken on this topic in relation to the Mediterranean areas. For that reason, this thesis aims to make an analysis on different scales of the effects of climate change on the area of the Mediterranean basin:

At European scale, in chapter 1, will be presents a land suitability map of the vitiviniculture area under climate change conditions. The map was developed starting from three bioclimatic indicators (Huglin Index, Cool Night Index and Dryness Index) and soil characteristics (slope and depth).

At national scale (Italy), in chapter 2, will be evaluate the impact on grapes due to the climate change studying the phenological aspect of Vitis Vinifera L. This part discusses how different phenological models have been tested in order to represent, as well as possible, the annual growth cycle of grape.

At regional scale (Sardinia), in chapter 3, will be describes how this research simulated the impact of climate change on vineyard using a crop-model (STICS) in order to give some information about modification of yield rate. In addition, the research simulated different adaptation and mitigation strategies in terms of crop management so as to suggest, where possible, different approaches in grapevine cultivation.

Chapter 2: Grapevine land suitability

Introduction

The land suitability process was developed by the FAO in the 80's of the 20th century to provide a tool for decision making. With such a process, it is possible to evaluate the fitness of a specific land for a distinct use.

Land evaluation is a process useful to predict land performance over time according to specific kinds of use (FAO, 1976).

Similarly, in agriculture the land suitability assessment predicts the potential and limitation of the land for a given crop production (Al Fajarat, et al. , 2015; Ayalew & Selassie, 2015).

According to Jones et al. (2012), vitivinicultural zoning is strictly dependent of climate conditions. For that reason, many studies have analysed the vineyard suitability considering only weather and climate variables (Fraga, et al., 2015; Kubach, 2012; Santos, et al., 2012). Other studies analyse the grapevine land suitability focusing on the importance of soil and characteristics of topography in viticulture (Watkins, et al., 1997).

In several examples, the land suitability process have resorted to GIS support, as it provides the basis for description and evaluation analysis (Bonfante, et al., 2011).

Many climatic indices have been proposed to study the spatial suitability of grapevine and to delimit areas with similar environmental factors so as to differentiate the specific viticultural zones.

This approach is used for several purposes. At the local scale, it characterises the region’s name by appellation of origin, such as French AOC (Vaudour, 2003) and DOC in Italy (Tomasi, et al. , 2012; AA. VV. , 2010; Failla, et al. , 2008) and Spain. At the global scale, the climate indices allow the comparison between viticulture regions in the world.

Generally, the most commonly used indices are temperature-derived as the Winkler index (WI) (Amerine and Winkler 1944), the duration of the growing period in degree-days, GDD (Winkler et al. 1974), the growing season temperature, GST (Jones 2006), the heliothermal index (HI) (Huglin 1978), the biologically effective degree-day index (BEDD). Tonietto & Carbonneau (2004) developed a research tool in which synthetic indices, such as Dryness Index (DI), Heliothermal Index (HI) and Cool night Index (CI), were combined through a Multicriteria Climatic Classification System (Géoviticulture MCC System) to characterize worldwide grape-growing regions. Different authors have utilized this approach to improve the knowledge and identify future adaptable vineyard regions (Fraga, et al., 2014; Irimia, et al., 2013; Tonietto, et al., 2010; Vuković, et al., 2010). Hall and Jones (2010) in Australia and Jones et al. (2010) in the west of the USA used different combinations of indices, such as GST, GDD, HI and BEDD to characterise winemaking regions.

In this framework, the aim of this study is to combine some climatic indices with soil information in order to provide a new method to analyse land suitability for grapevine in Mediterranean areas. In addition, the impact of climate change has been considered in order to analyse projected shift in suitable areas for grapevine cultivation, considering the new RCP climate scenarios and climate data at high resolution.

Materials and methods

The land suitability analysis for grapevine is composed by the combination of bioclimatic indices, calculated for present and future climate conditions, and pedological characteristics.

Bioclimatic index

Three bioclimatic indices have been used to characterize the grapevine suitability, according to a scheme developed by Tonietto & Carbonneau (2004): Huglin Index, Dryness Index and Cool night Index.

The **Huglin Index (HI)** is a climate index developed by Huglin (1978) to express the heliothermal potential of the vineyards’ climate; temperatures are calculated in the period of the day in which the metabolism of grapevine is more active; the index considers also a correction factor in order to relate the length of the day and the latitudes. HI relates the thermal requirements of different grape varieties to the physiological development.

$$HI = \sum_{n=01.04}^{30.09} \frac{[(T-10)] + [(Tx-10)]}{2} d$$

T= daily average temperature,
Tx= daily maximum temperature,
10=T base temperature at 10°C
d= coefficient of the length of the day

Table 2. 2: d coefficient value according to latitude degree

Latitude	≤40°00’	40°01’- 42°00’	42. 01’- 44°. 00’	44. 01’- 46°. 00’	46°. 01’- 48°. 00	48. 01’- 50°. 00’
d coefficient	1. 00	1. 02	1. 03	1. 04	1. 05	1. 06

The **Cool night Index (CI)** is a viticultural climate index developed to estimate the mean minimum night temperatures at the end of the vegetative cycle (September in the Northern Hemisphere), in correspondence to the grape maturation period (Tonietto, 1999).

In the Northern Hemisphere CI is calculated as the minimum air temperature in September (mean of minima), in °C.

The **Dryness Index (DI)** used here is a modification of the soil index (Riou, 1994), adapted to grapevine. The Riou soil index considers climatic demands of a standard vineyard, evaporation from bare soil and rainfall, including surface runoff and drainage, over the growing season, whereas the DI estimates potential water availability for grape in soil in relation to dryness level.

$$\mathrm{DI} = \mathrm{W}_0 + \mathrm{P} - \mathrm{T}_\mathrm{v} - \mathrm{E}_\mathrm{s}$$

W_0= initial useful water reserve in the soil (mm) assume equal to 200 mm
P= precipitation (mm)
T_v=potential transpiration of the vineyard (mm)
E_s= direct evaporation from soil (mm)

The potential transpiration of the vineyard is calculated as T_v= ETP*k, where ETP is the potential evapotranspiration and k is the coefficient of radiation absorption by vine plant.

The direct evaporation from soil is determined by the following formula:

$$\mathrm{Es}=\frac{\mathrm{ETP}}{\mathrm{N}}(1\text{-}k)*\mathrm{JPm}$$

Where ETP is the potential evapotranspiration, N is the number of days in the month, k is the coefficient of radiation absorption by vine plant, JPm is the rainfall per month in mm/5.

The ETP equation used in this study is the standardized reference evapotranspiration rate for short canopies proposed by Allen et al. (2005).The k values adopted for the Northern Hemisphere assume that k = 0. 1, for April, 0. 3 for May and 0. 5 for the months from June to September.

The Dryness Index is calculated, every month, from the 1st of April to the 30th of September and the DI is the corresponding value of W obtained at 30 September.

These indices allow locating suitable viticultural regions according to varietal needs, as summarized in the tables below (Tabs. 2.2, 2.3, 2.4).

Table 2. 3: description of Huglin Index (HI) classes

Index	*Acronym*	*Class interval*	*Class of viticultural climate*	*Wine varieties (i.e.)*
HI	HI +3	HI >3000	Very warm	Absence of heliothermal limitation for grapes maturity, sometimes is possible to have more than one harvest a year
	HI +2	2400 ≤ HI <3000	Warm	Late varieties with some associated risks of stress
	HI +1	2100 ≤ HI < 2400	Temperate warm	Grenache, Mourvèdre, Carignan
	HI -1	1800 ≤ HI <2100	Temperate	later varieties, such as Cabernet-Sauvignon, Ugni Blanc and Syrah
	HI -2	1500 ≤ HI < 1800	Cool	Riesling, Pinot noir, Chardonnay, Merlot, Cabernet Franc
	HI -3	HI ≤ 1500	Very cool	very early/early varieties able to reach maturity, especially the white varieties i. e. Muller-Thurgau, Pinot blanc, Gamay, Gewurztraminer

Table 2.3: description of Cool Night Index (CI) classes

Index	*Acronym*	*Class interval*	*Class of viticultural climate*	*Description*
CI	CI +2	≤ 12	Very cool nights	Low night temperature conditions ensure a good level of grape ripening for a several varieties
	CI +1	12 < CI ≤ 14	Cool nights	According to the precocity of grape varieties, ripening occurs under more or less cool conditions
	CI -1	14 < CI ≤ 18	Temperate nights	Later varieties ripe under lower night temperature conditions than the early varieties
	CI -2	> 18	Warm nights	High nocturnal temperatures that have an effect on berry colour and aromatic potential

Table 2.4: description of Dryness Index (DI) classes

Index	*Acronym*	*Class interval*	*Class of viticultural climate*	*Description*
DI	DI +2	≤ -100	Very dry	The potential dryness is marked, the stress effects are frequent and the irrigation is practiced, sometimes mandatory.
	DI +1	-100 < DI ≤ 50	Moderately dry	Some dryness level may potentially face. Condition favourable to maturation phase. Irrigation is practiced in certain cases. Around DI < 50mm, correspond the Mediterranean-type climate regions, with water deficit in the summer.
	DI -1	50 < DI ≤ 150	Sub-humid	Over 50 mm there is absence of dryness, with frequent summer dryness
	DI -2	> 150	Humid	Over 150 mm there is absence of dryness, with a high level of water balance availability

The climate data used to calculate the three bioclimatic indices are daily data from the Regional Climate Model (RCM) COSMO-CLM (Bucchignani et al. , 2014) with a spatial resolution of 14 Km dynamically downscaled from the Global Circulation Model (GCM) CMCC-MED for the Mediterranean basin (13W-46E; 29-56N).

The bioclimatic indices were calculated for the baseline period (1976-2005) and for three future periods: 2020 (2006-2035), 2050 (2036-2065), and 2080 (2066-2095). The climate scenarios Representative Concentration Pathway (RCP) 4.5 and 8.5 have been considered for future climate projections from 2006 to 2095.

The formulas of the HI and CI indices were re-written with the Climate Data Operators (CDO) software (Version 1. 6. 9- May 2015), the DI index was re-write with R software 3.2.0 version (R Core Team, 2015) using ncdf4 package version 1.12 (Pierce D. , 2014). After that, the climate netCDF data were ran with the script cited above in order to obtain the netCDF file for each index in the seven different periods: for the baseline (1976 - 2005) and for three future periods (2006-2035; 2036-2065; 2066-2095) and two RCP scenarios (4. 5, 8. 5). The resulting netCDF files represent the mean value of the thirty-year considered. These bioclimatic netCDF were then elaborated in ArcGis 10.2 in order to obtain the raster maps for every index, used for the land suitability assessment.

Pedologic characteristics

According to Bucelli & Costantini (2006) and Failla et al. (2008) the grapevine is able to grow in very different soil conditions. Thanks to the employment of rootstocks and agronomic management, it is possible to cultivate grape, more or less, in several territory. Nevertheless, the authors have identified some physical aspects of the soil that can influence the adaptability of the vineyard to a specific environment. In this work, only the two principal factors that may limit the grapevine growth are considered: soil slope, expressed in percentage, and the soil depth, expressed in centimetres (Table 2. 5).

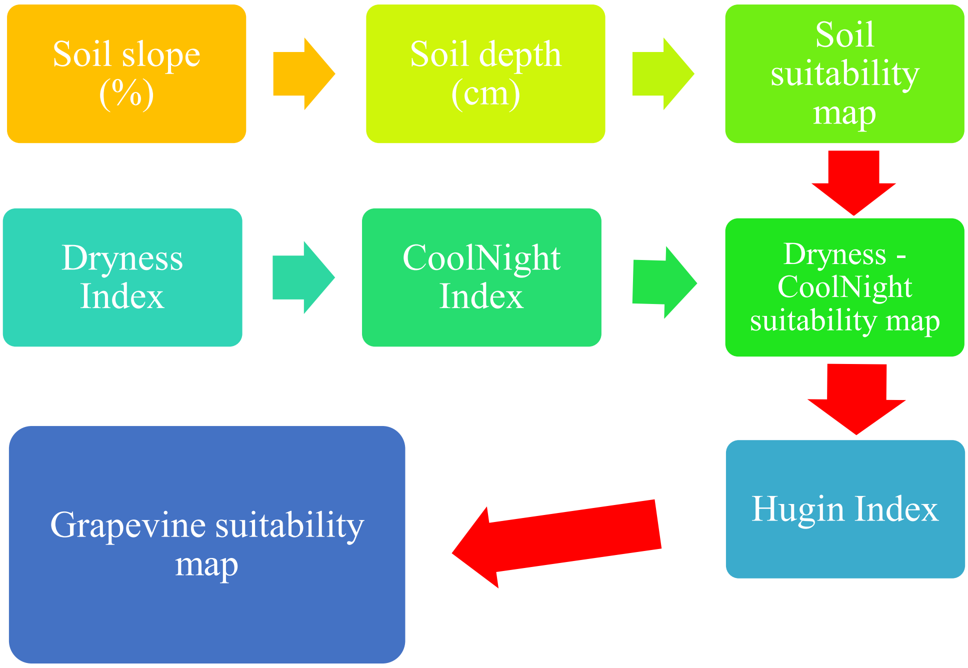
Table 2. 4: suitability class for slope and soil depth factors

	Aptitude classes			
Variable	S1	S2	S3	N
Slope (%)	≤ 14	15 ÷ 21	22 ÷ 35	> 35
Soil depth (cm)	> 100	100 ÷ 50	49 ÷ 25	< 25

For this part, the data were deduced by ESDB derived data (Hiederer, R, 2013a,b) for soil depth value and by Global 30 Arc-Second Elevation (GTOPO30) for slope. These two dataset were remapped from 1km of resolution to the netCDF files with grid dimensions of 14 km.

The following scheme (Scheme 2.1) summarizes the methodological steps that constitute the applied methodology for land suitability classification.

Scheme 2.1: grapevine land suitability method



The suitability classes are organized starting from suitable environmental conditions for grapevine, ranking from lowest to highest limiting factors in each index and variables (soil depth and slope) interval. In the table below (Tab. 2.6) the class adopted for DI and CI index are summarised, HI remains as a categorized index due to the varietal specificity expressed. Soil classification is reported in table 2.5

Table 2.6: bioclimatic indices classification and relative suitability class

Index		*Class*	*Suitability Class*
CI			
	Temperate nights	14 ÷ 18	S1
	Cool nights	12 ÷ 14	S2
	Very cool nights	≤ 12	S3
	Warm nights	> 18	N
DI			
	Moderately dry	-100 ÷ 50	S1
	Sub-humid	50 ÷ 150	S2
	Very dry	≤ -100	S3
	Humid	> 150	N

The subsequent combinations of suitability classes are developed assuming the lowest class as a limiting factor.

Results and discussion

The results obtained from this research study are presented in form of maps of the different variables.

Soil suitability

The soil analysis map allowed identifying the suitable area for slope (Fig. 2.1), for depth (Fig. 2.2) variables and, based on these maps, the soil suitability map was obtained using a topographic overlay (Fig. 2.3).

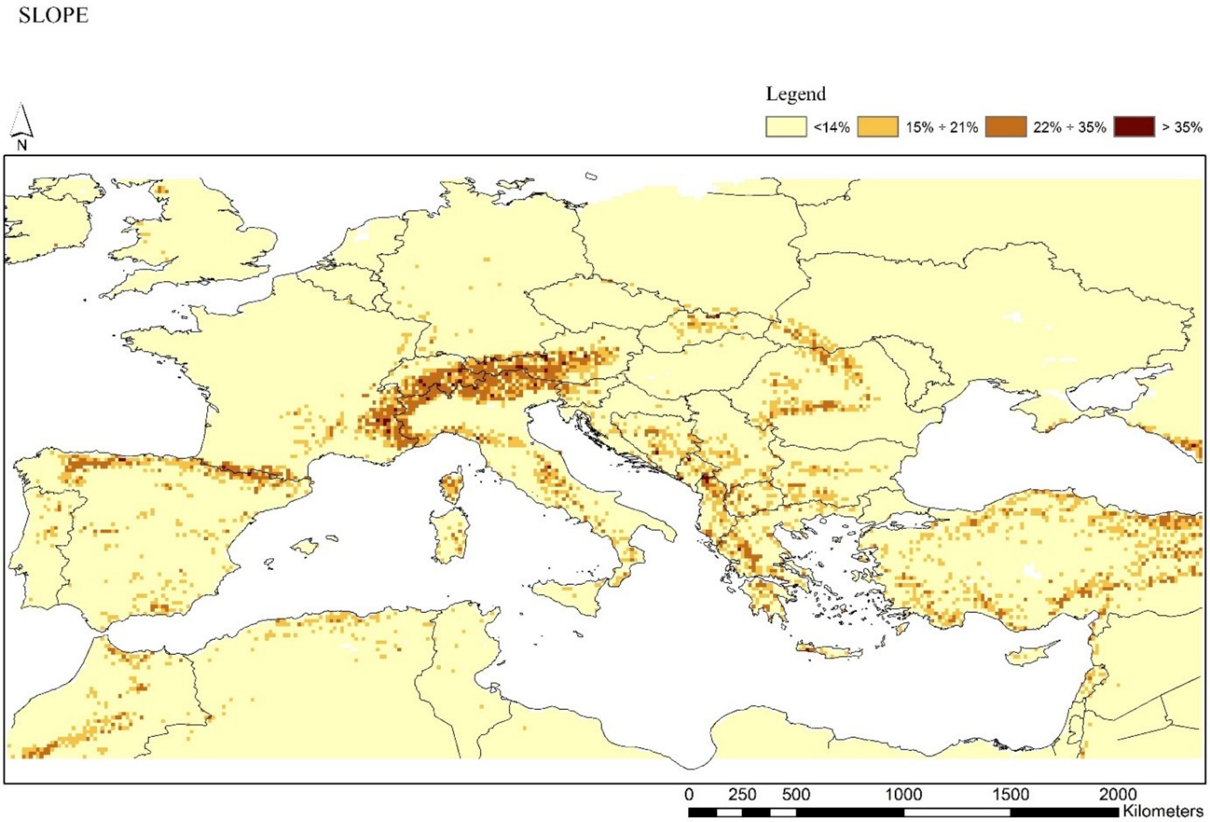


Figure 2.1: soil suitability: slope classes (%) map

The slope suitability map identified four different classes: S1 with a slope lower than 14%, S2 with a slope included between 14% and 21%, S3 with a slope included between 22 and 35%, and the N class with the slope value higher than 35%. The major part of the area resulted in S1 class with value of slope <14%. The other classes are distributed along the mountains chains.

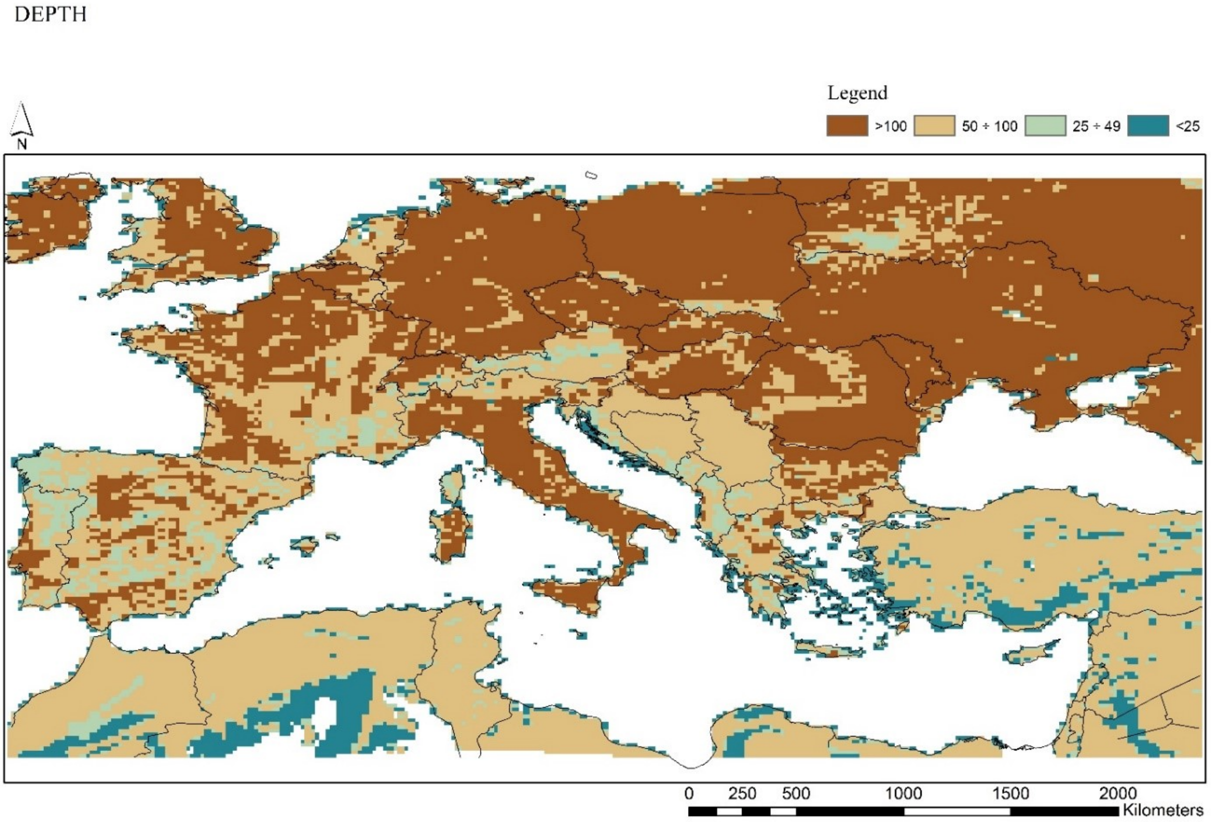


Figure 2.2: soil suitability: depth (cm) classes map

The four classes identified in the depth suitability map are described in table 2. 5.

In a similar way to the slope suitability map, the S1 class (depth > 100 cm) covers the major part of the European area; the second suitability class (S2) with depth value between 50 and 100 cm was also well represented.

The other two classes, S3, with depth included between 49cm and 25 cm, and N, with depth lower than 25 cm, follow the mountains chains and the coast boundaries.

The soil suitability map (Fig. 2. 3), that shows different classifications of soil attitude for grape cultivation, was obtained after an overlay mapping between slope and depth soil suitability maps. The S1 and S2 classes result as the most diffuse all around the analysis area; S1 is with deeper soil and relatively flat. On the other hand, the N class comprises the steepest and the thinnest soils.

In the middle there are the S2 and S3 classes, where grape cultivation is possible but with some agronomical limitations. In these classes it will be necessary to adopt particular management practices according to the slope (terracing strategies) or the depth (rootstocks and apt varieties).

SOIL SUITABILITY MAP

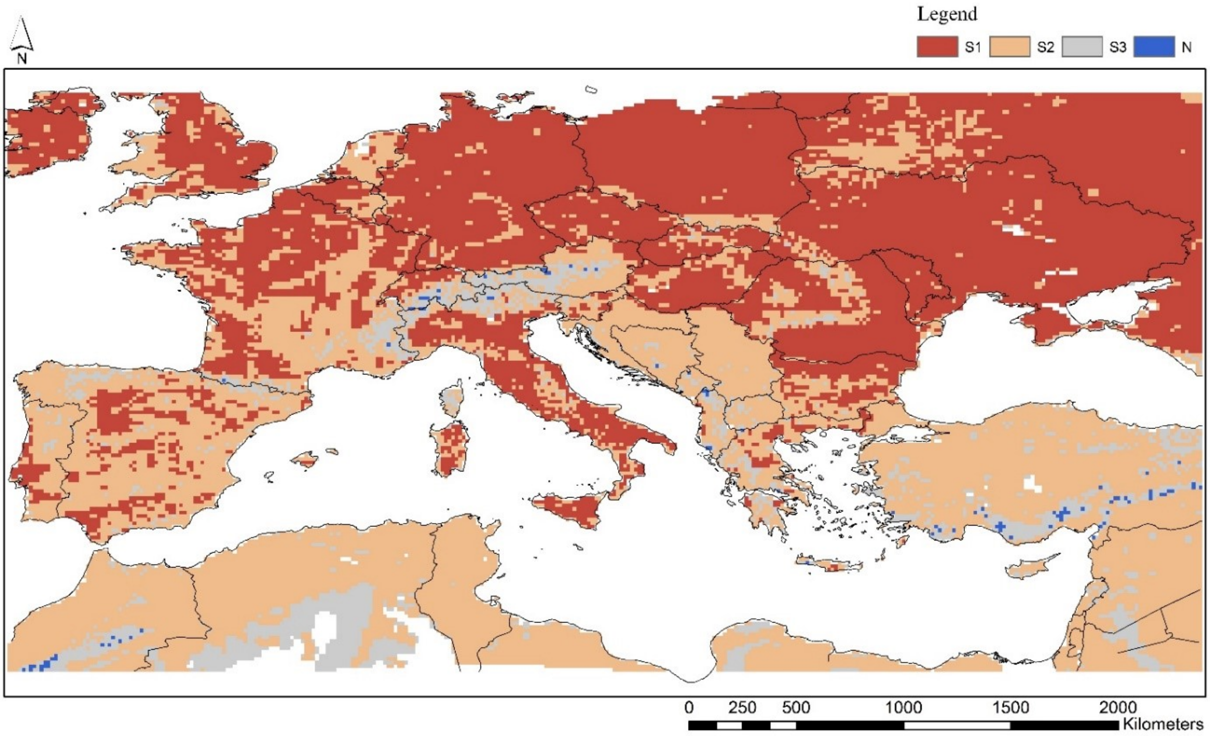


Figure 2.3: soil suitability map

Dryness- Cool Night indices suitability

CI index

The Cool Night Index for Baseline period (Fig 2. 4) showed a widespread area where the minimum temperatures of September are very cool. The remaining areas, around the Mediterranean basin and the Black sea basin, assume all the other three CI values. It is possible to distinguish a gradient of temperature from north to south of these basins, starting from the mountain chains and hills with a cool climate, dropping to temperate and warm night in the south of the area.

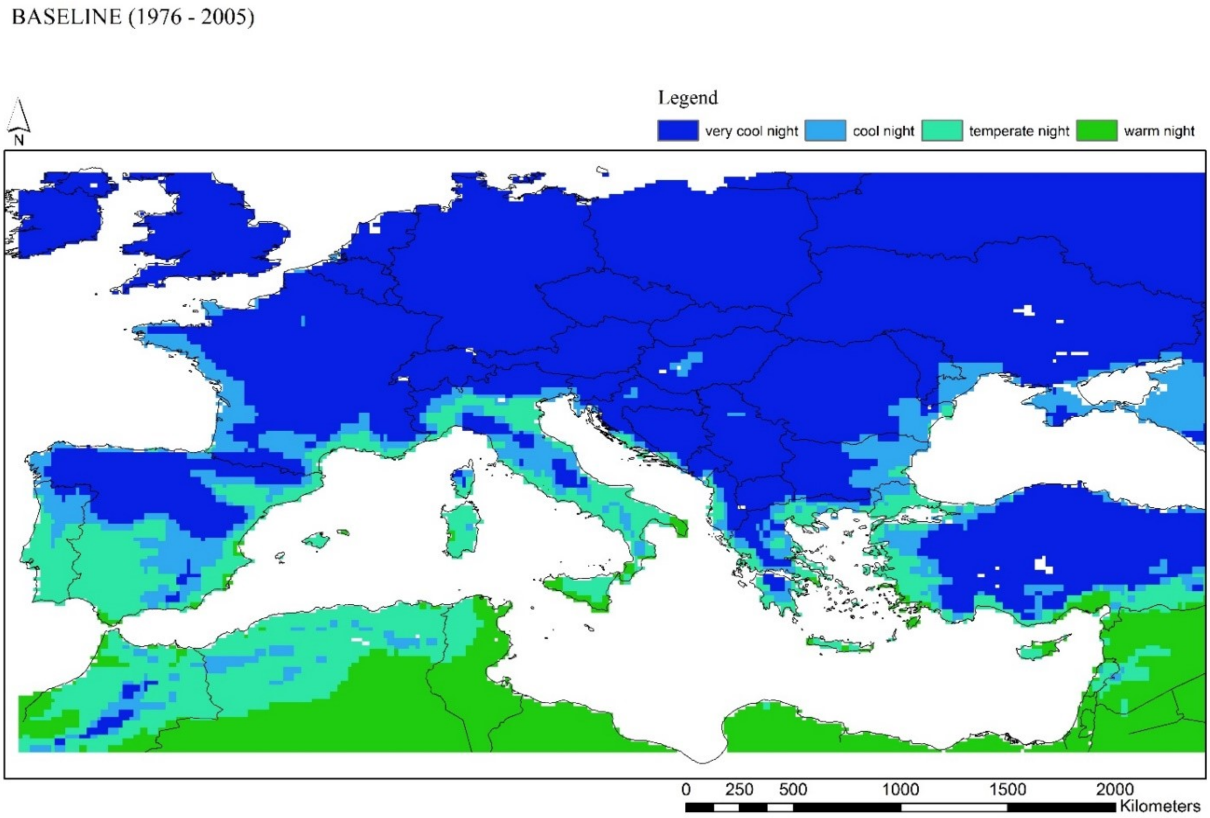
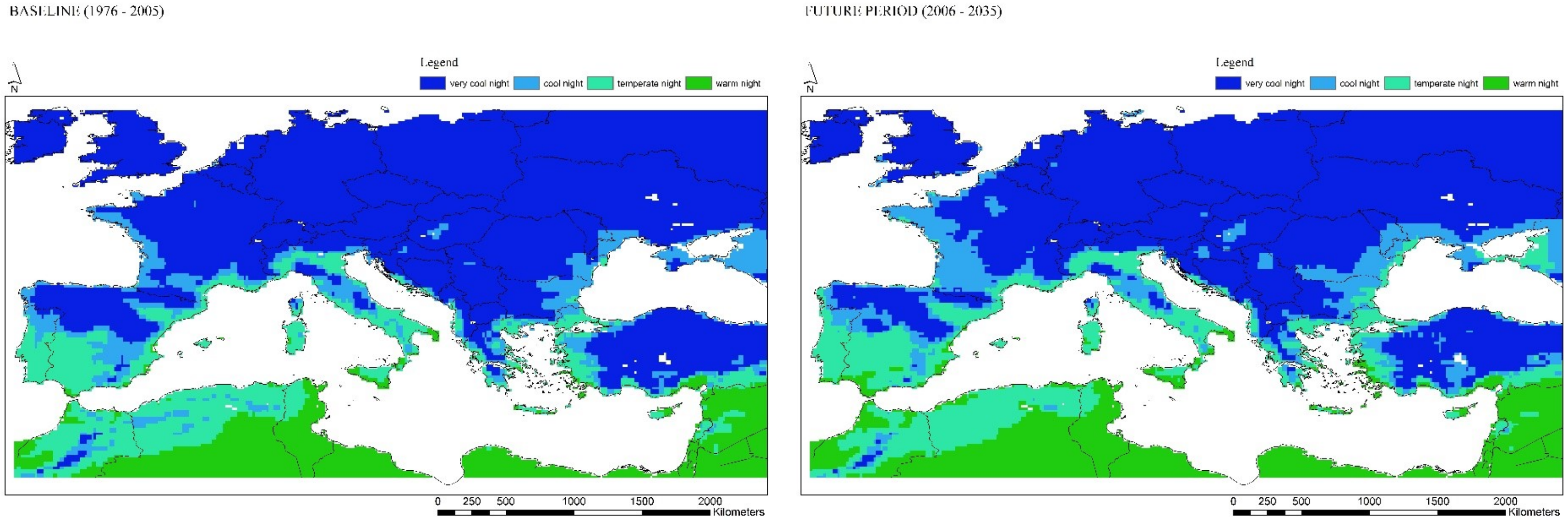

BASELINE (1976 - 2005)

Figure 2.4: CI index - mean of historical period (1976-2005)

According to the CI index classifications the temperate night area correspond to a range of temperature between 14°C and 18°C that allow the ripening for the major part of the grapevine varieties. For this reason, such temperature interval was classified as S1 on the suitability map. The S2 class considers the area in which the temperature of the night are cool and allow the ripening in accordance with the precocity of the plant. The very cool night areas are classified as S3 because such temperature conditions ensure a good level of ripening but in sunlit zones. The N class involved the area where the high minimum temperatures may affect grape characteristics.

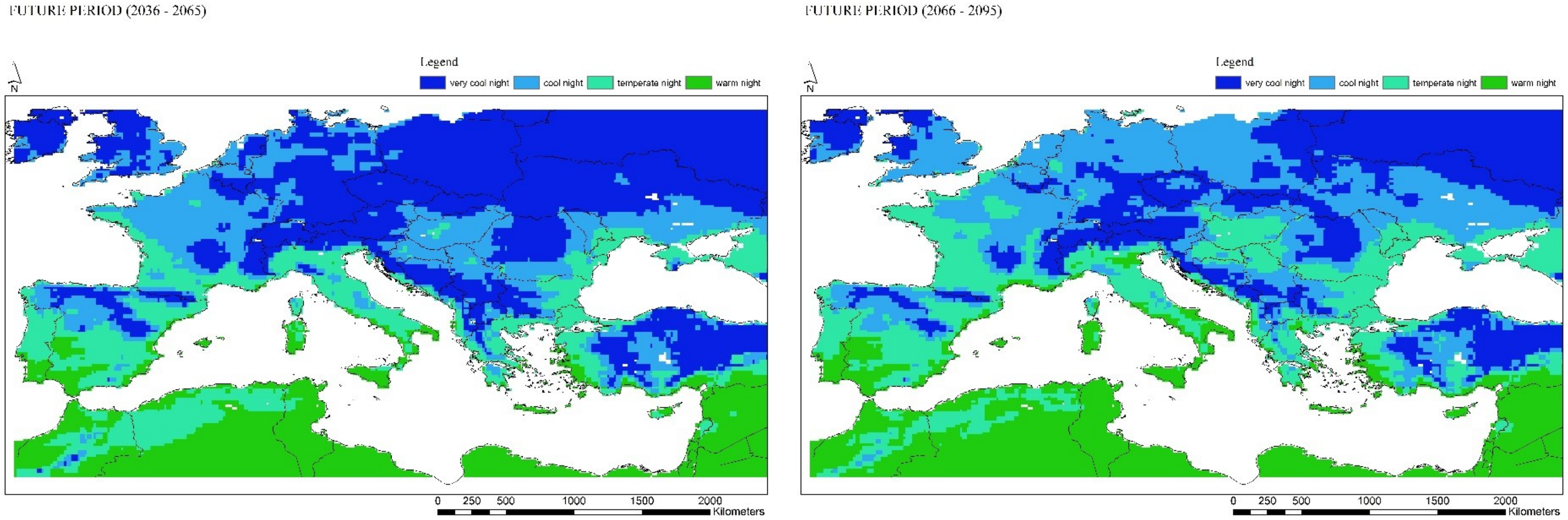
For the subsequent periods, similarly to the HI index, the temperature registered an upwards modifications, higher in RCP 8.5 than in RCP 4.5 (Figures 2.5, 2.6)

As Malheiro et al. (2010) already observed, in future scenarios, the CI index will register a significant increase at low-altitude zones in the Mediterranean Basin. Such modifications might have a negative impact on grapevine production as concerns quality.



BASELINE (1976 - 2005)

FUTURE PERIOD (2006 - 2035)



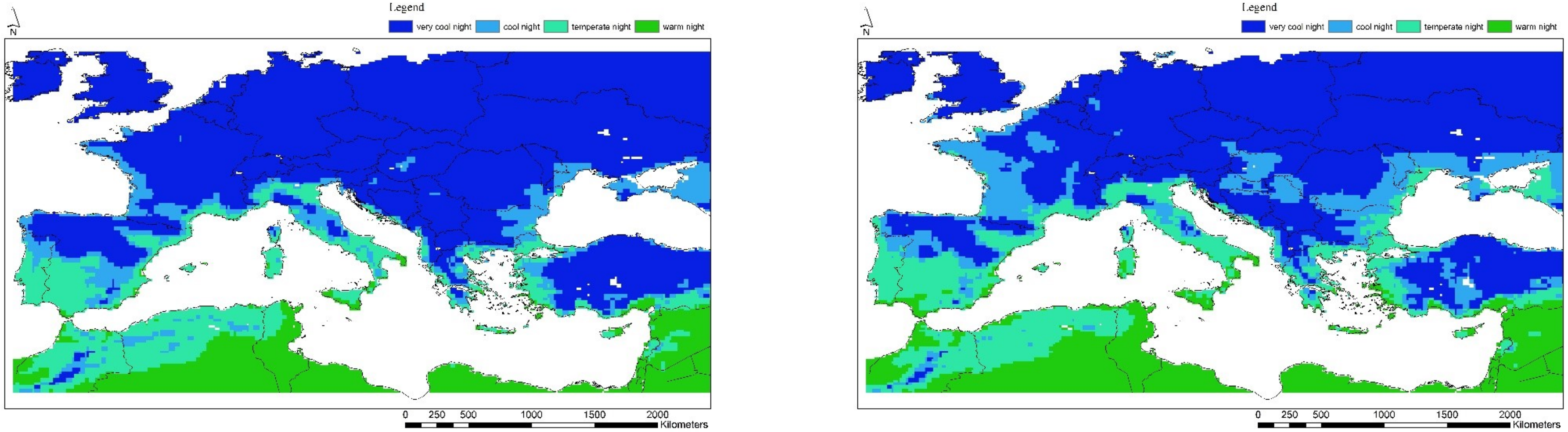
FUTURE PERIOD (2036 - 2065)

FUTURE PERIOD (2066 - 2095)

Figure 2.5: CI index maps - comparison between BASELINE and RCP 4.5 scenarios

BASELINE (1976 - 2005)

FUTURE PERIOD (2006 - 2035)



FUTURE PERIOD (2036 - 2065)

FUTURE PERIOD (2066 - 2095)

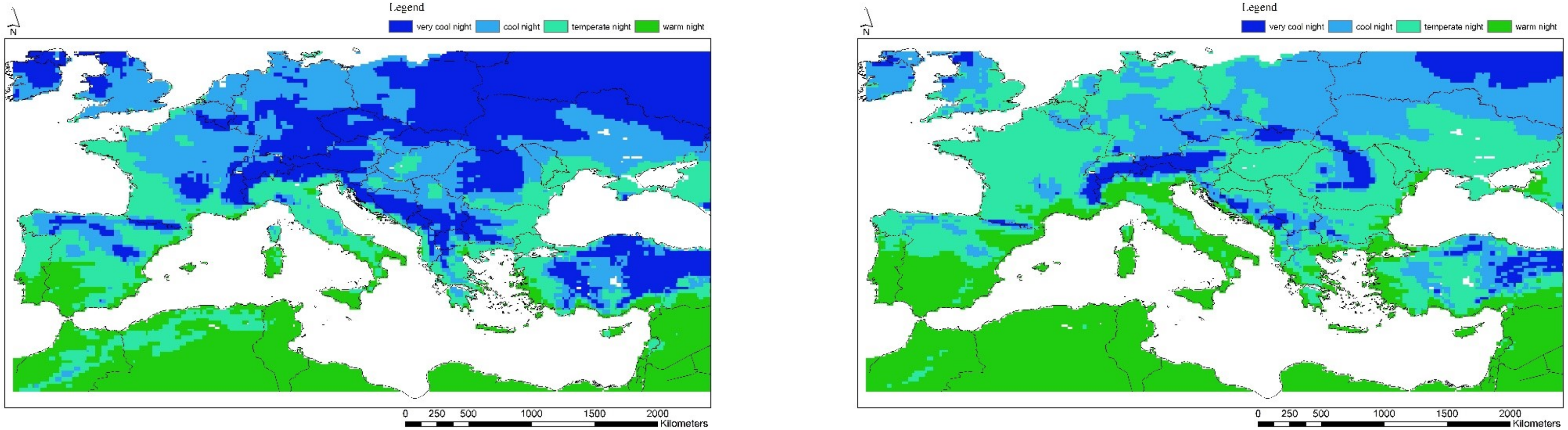


Figure 2.6: CI index maps - comparison between BASELINE and RCP 8.5 scenarios

DI index

With regard to DI, the whole area is subdivided into four classes that create, also here, a gradient of intensity. In Baseline (1976 – 2005) (Fig. 2. 7), starting from the south, it is possible to shown a diffuse area where dryness might be a limitation (below -100 mm); in correspondence of the sea basins the DI results moderately dry, with values between -100 mm and 50 mm of available water in the soil at the 30th of September. The sub- humid and humid zones appear peculiar to the northern European areas and in correspondence of mountain chains.

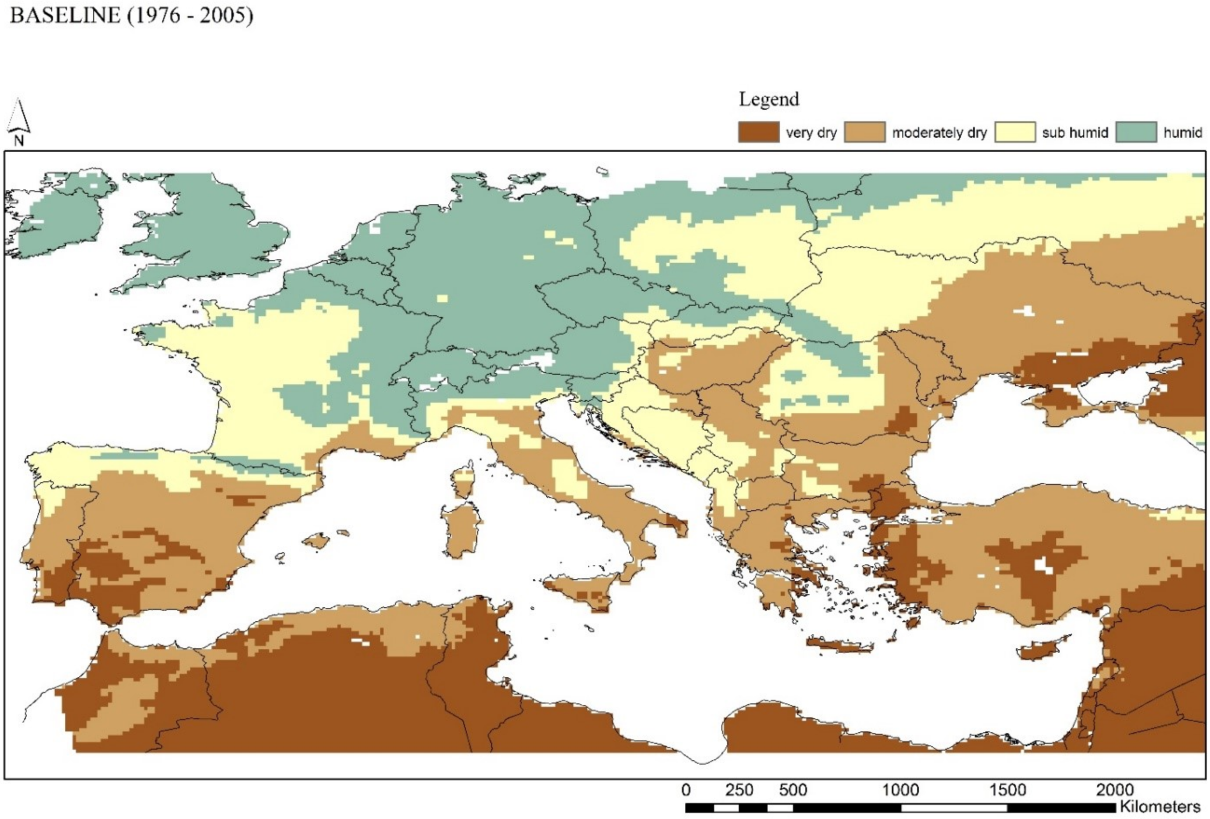

BASELINE (1976 - 2005)

Figure 2.7: DI index - mean of historical period (1976-2005)

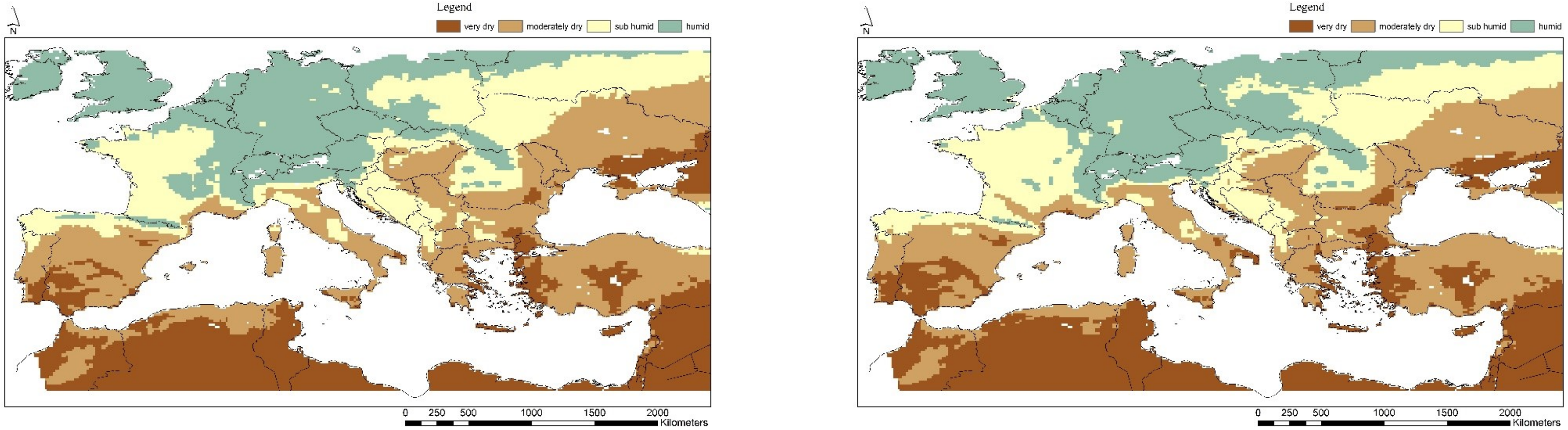
According to Tonietto & Carbonneau 2004, moderately dry conditions are considered the most favorable for the production of high quality wines, for this reason this study has considered such conditions as S1 class.

The sub-humid area, with a dryness index between 50 mm and 150 mm, was classified as S2. Because both excessive dryness (DI < –100 mm) and excessive humidity (DI > 150 mm) might have detrimental impacts on grape development, they are classified as S3 and N respectively.

Regarding future periods, drying will increase in most European areas, as shown also by Malheiro et al. (2010) (Figures 2.8, 2.9).

BASELINE (1976 - 2005)

FUTURE PERIOD (2006 - 2035)



FUTURE PERIOD (2036 - 2065)

FUTURE PERIOD (2066 - 2095)

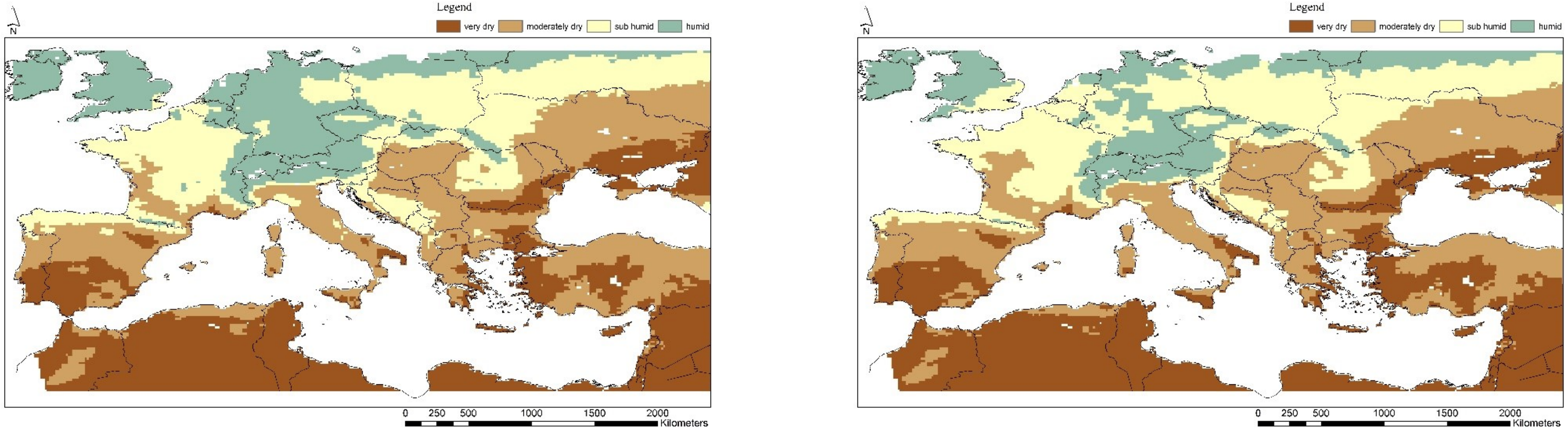
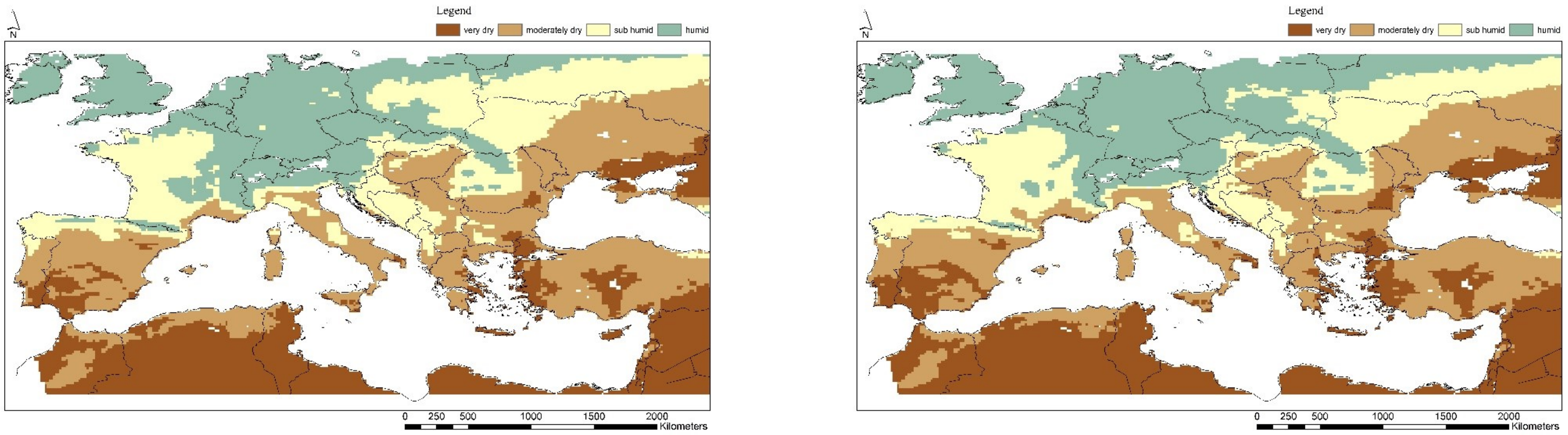
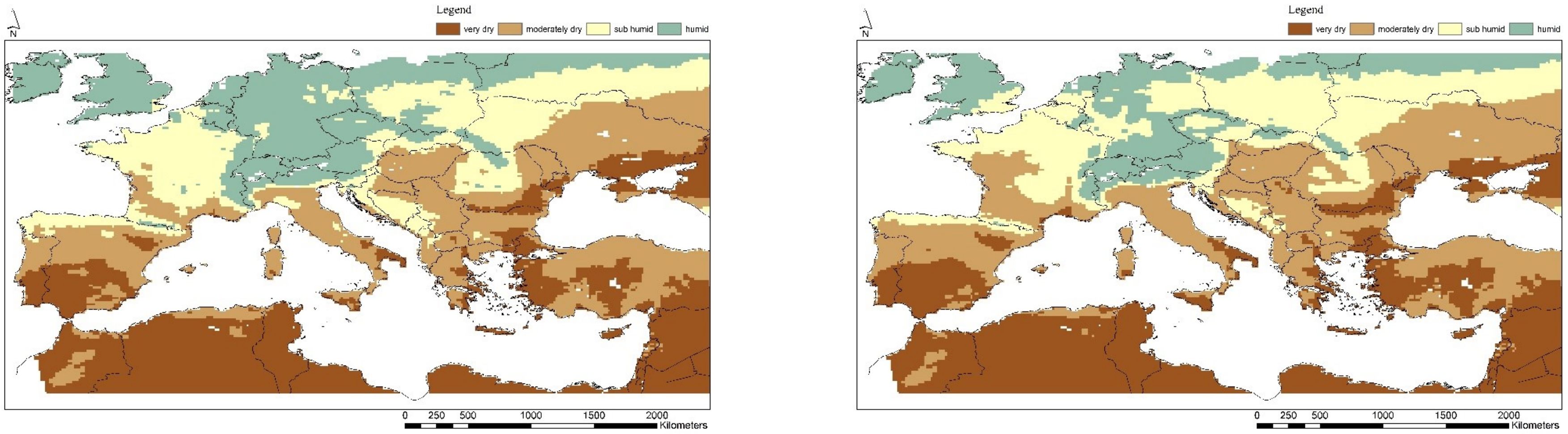


Figure 2.8: DI index maps - comparison between BASELINE and RCP 4.5 scenarios


BASELINE (1976 - 2005)

FUTURE PERIOD (2006 - 2035)


FUTURE PERIOD (2036 - 2065)

FUTURE PERIOD (2066 - 2095)

Figure 2.9: DI index maps - comparison between BASELINE and RCP 8.5 scenarios

Dryness – CoolNight suitability map

In this section, the dryness index and the cool night index were combined in order to obtain a suitability map of the relationship between the available water soil content and the minimum temperature of the area. The obtained maps show that the European area is subdivided into four main areas where the N suitability class covers the major part of the whole area, in correspondence of humid area with very cool nights and warm nights, and of very dry area with warm night temperatures (Tab 2.7). In the middle, a gradient of classes from the inner part to the coast of the sea basins describes the suitability areas. It is particularly interesting to see that the most suitable areas are located along the coasts of the Mediterranean basin and in the Iberian Peninsula. (Fig 2.10)

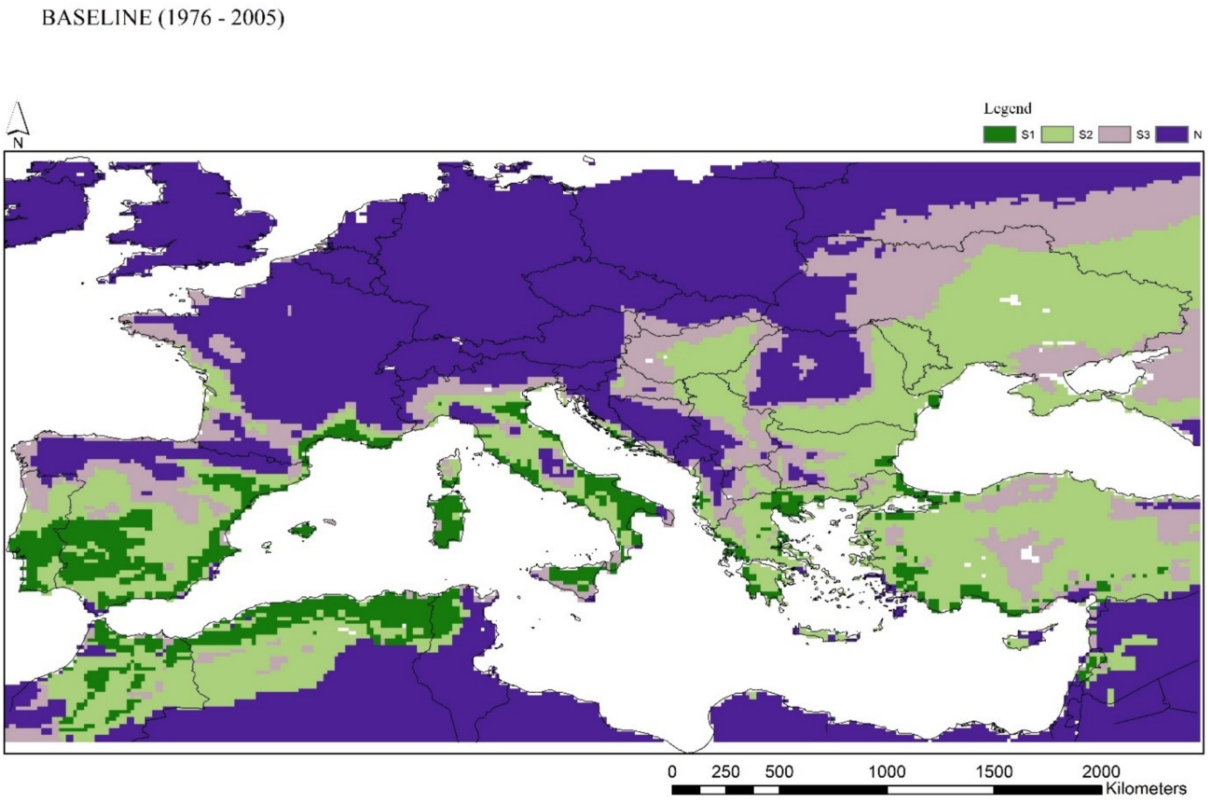
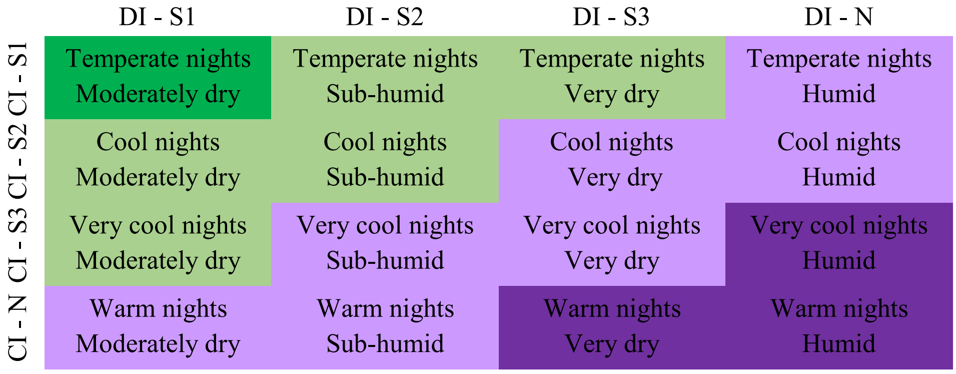

BASELINE (1976 - 2005)

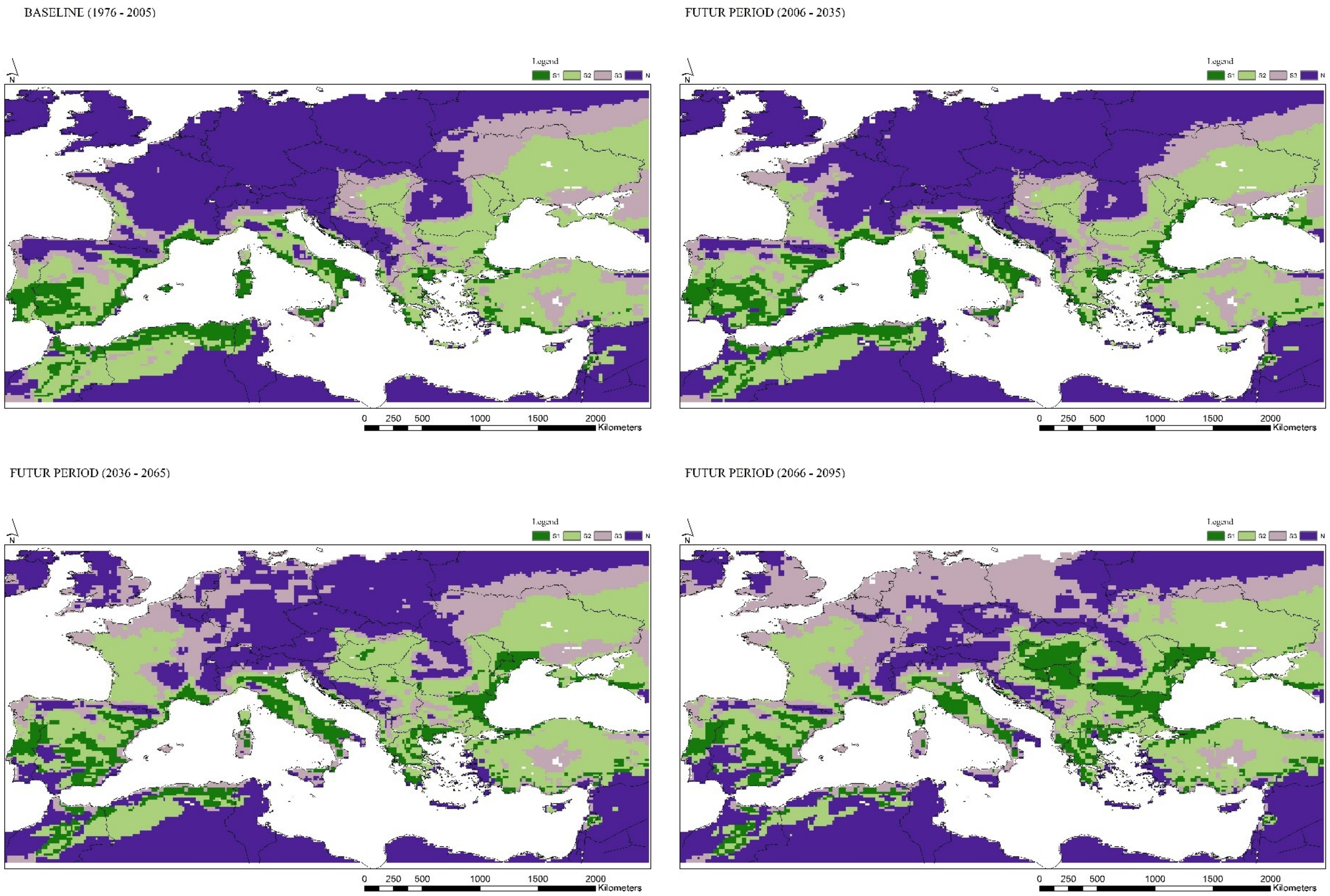
Figure 2.10: DI-CI suitability map - mean of historical period (1976-2005)

Table 2.7: suitability class of DI-CI map



	DI - S1	DI - S2	DI - S3	DI - N
CI - S1	Temperate nights Moderately dry	Temperate nights Sub-humid	Temperate nights Very dry	Temperate nights Humid
CI - S2	Cool nights Moderately dry	Cool nights Sub-humid	Cool nights Very dry	Cool nights Humid
CI - S3	Very cool nights Moderately dry	Very cool nights Sub-humid	Very cool nights Very dry	Very cool nights Humid
CI - N	Warm nights Moderately dry	Warm nights Sub-humid	Warm nights Very dry	Warm nights Humid

In the subsequent periods, both in the RCP 4.5 and in the RCP 8.5 scenarios, the suitability classes registered a northward shift. The N class will drastically be reduced in the north of Europe but it will increase in the south; the S1 class will move in correspondence of the best environmental conditions for the grapevine growth. The S2 and S3 classes will colonize the north-west of Europe in parallel to the decrease of the N class. In RCP 8.5 these reductions confine the N class only in correspondence of the mountain chains and the warmest and driest areas (Figures 2. 11, 2. 12).



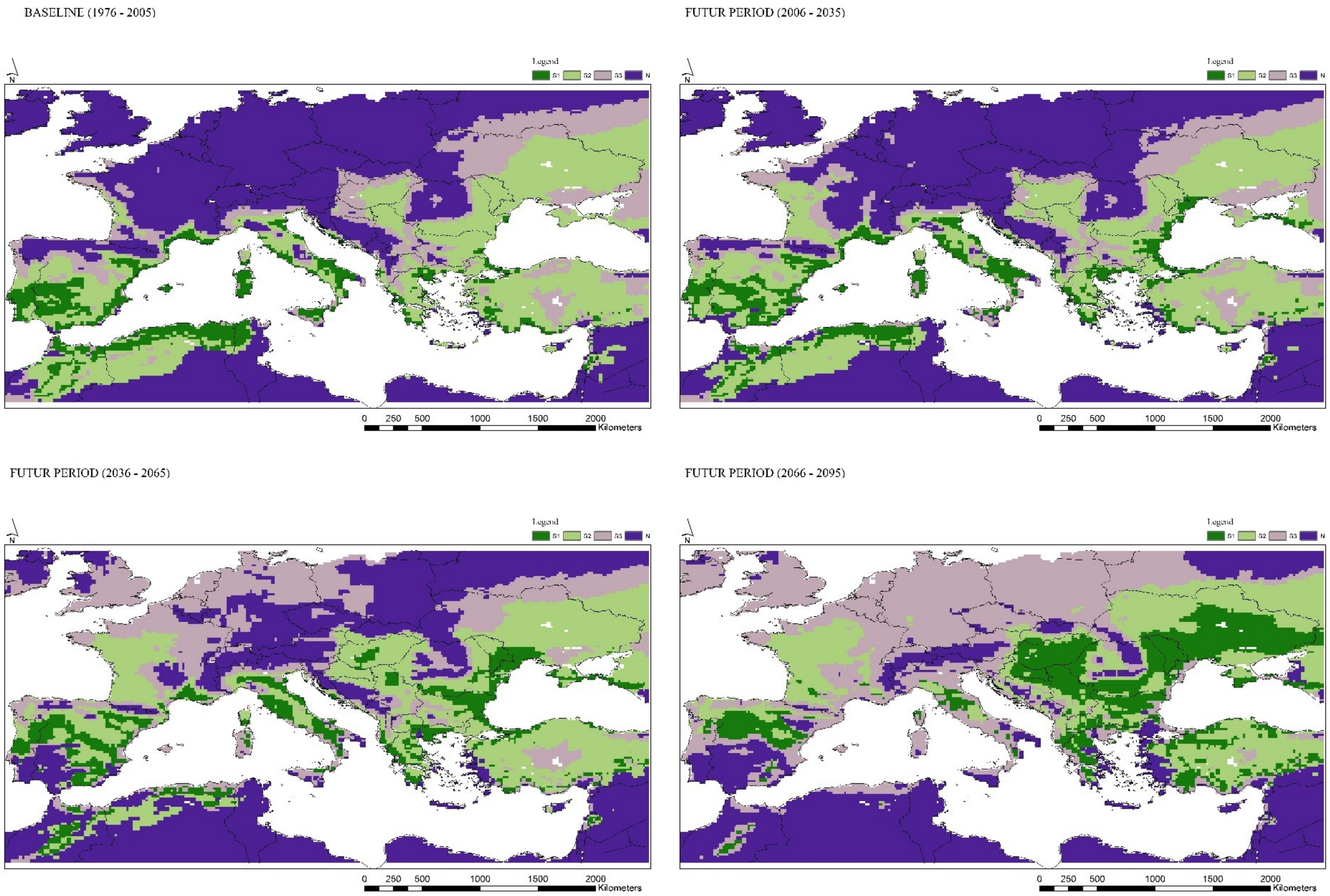
BASELINE (1976 - 2005)

FUTUR PERIOD (2006 - 2035)

FUTUR PERIOD (2036 - 2065)

FUTUR PERIOD (2066 - 2095)

Figure 2.11: DI-CI index maps - comparison between BASELINE and RCP 4.5 scenarios



BASELINE (1976 - 2005)

FUTUR PERIOD (2006 - 2035)

FUTUR PERIOD (2036 - 2065)

FUTUR PERIOD (2066 - 2095)

Figure 2.12: DI-CI index maps - comparison between BASELINE and RCP 8.5 scenarios

HI index

The assessment at the macroclimate scale reveals that the viticulture of the Mediterranean basin was completely explained by the whole HI scale range. In figure 2.13, in fact, it is possible to see the HI values, calculated as a mean of historical period (1976-2005).

The European area under consideration is characterized by six levels of heliothermal potential, expressed by the classes of HI index, respectively as: very cold climate (≤ 1500), cold climate (1800 ≤ HI < 1500), temperate climate (2100 ≤ HI < 1800), temperate-warm climate (2400 ≤ HI < 2100), warm climate (3000 ≤ HI < 2400) and very warm climate (> 3000). The prevailing HI classes of the wine regions are the middle class, corresponding to the range values between 1500 and 2400. The extreme classes, less than 1500 and up to 3000, described the boundaries of the area.

It is also possible to recognise a relation between the HI index values and the topography of the land. In correspondence of the mountain area and the high latitude territory, the HI value registers low values (very cool); on other hand, in the hilly areas it gives medium results (cool and temperate), and near the coast or plain areas in the low latitude zones the range of HI is high (warm and very warm). On the basis of this classification it is possible to find early and very early varieties at high latitude and in cooler climate conditions (Duchene and Schneider, 2005) while, on the other hand, the late varieties are situated in the southern areas.

BASELINE (1976 - 2005)

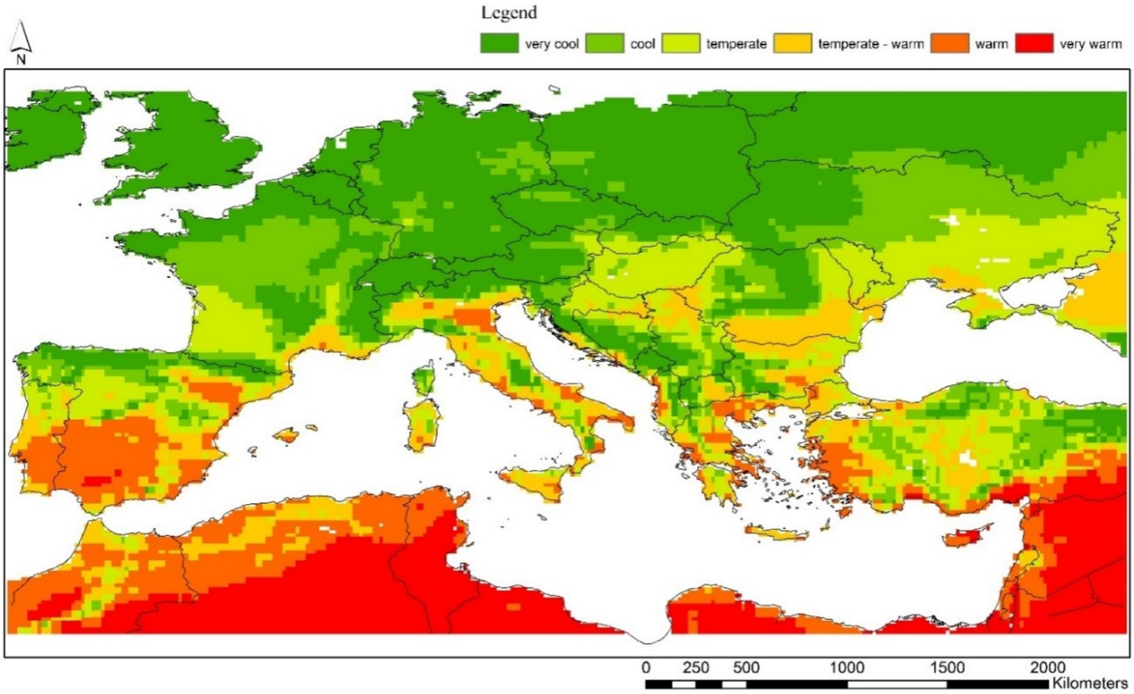


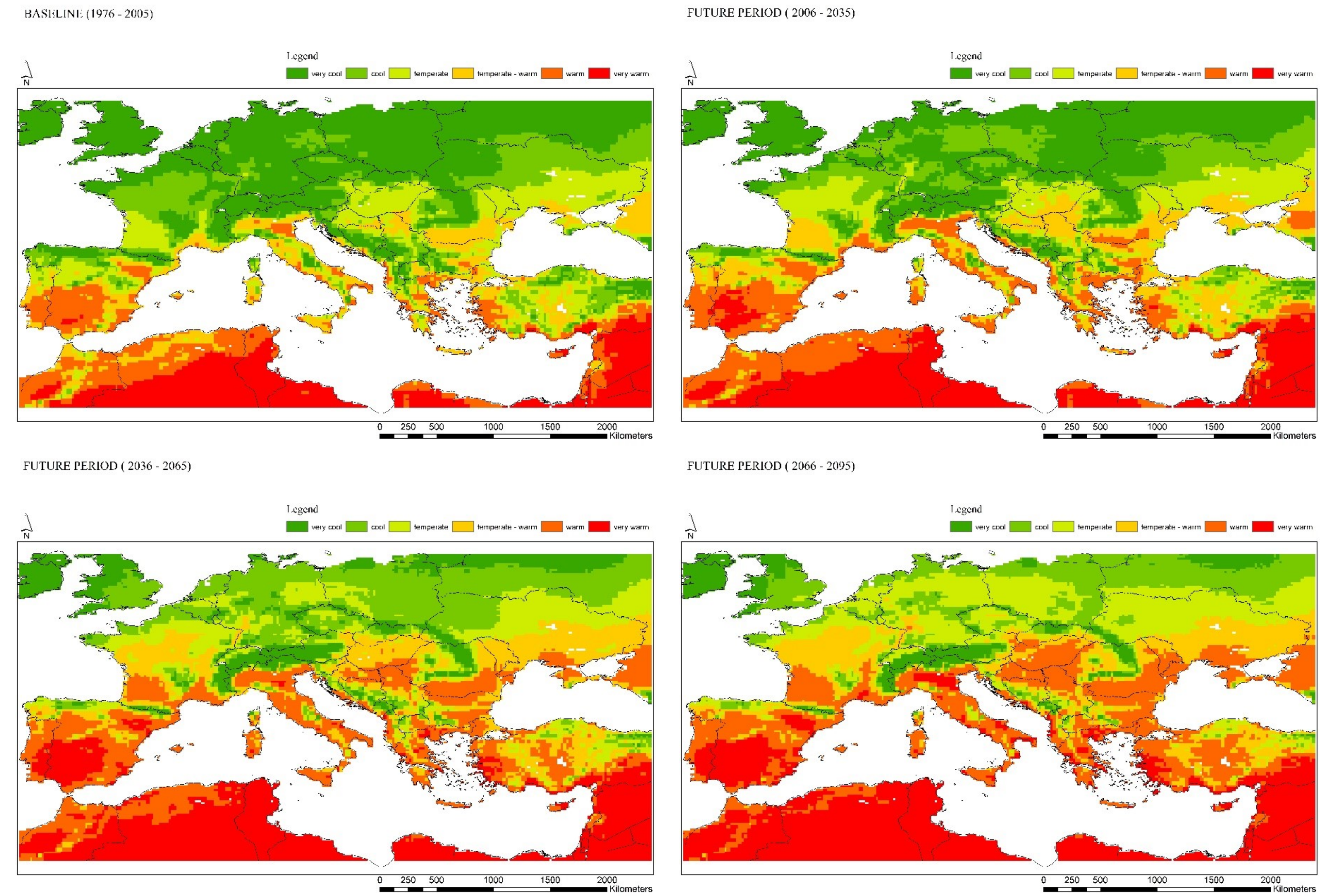
Figure 2.13: HI index - mean of historical period (1976-2005)

However, in the future this assessment might change. In the following pages are reported the HI maps calculated according to the two climate scenarios (RCP 4. 5 and RCP 8. 5) for the three future periods (2006-2035; 2036-2065; 2066-2095).

The future simulations give an idea of the modifications that the HI index will have as a result of climate change (Figures 2. 14, 2. 15), respect to the present condition. The maps show a general shift of the HI index classes, both in RCP 4.5 and in RCP 8.5. Particularly, the early and very early varieties will spread out in the north-east of Europe; on the other hand, the late varieties will likely be cultivated at mid-latitude.

These results are in accordance with Fraga et al. (2013), who underlined the arising of new suitable region for grapevine within the latitude belt 50-55° N.

Moreover, this shift in suitable areas for grapevine cultivation may determine a change in sugar potential of a vine variety, as stated by Malheiro et al. (2010) who underlined the physiological connection between temperature and the assessment of sugar potential of a vine variety.

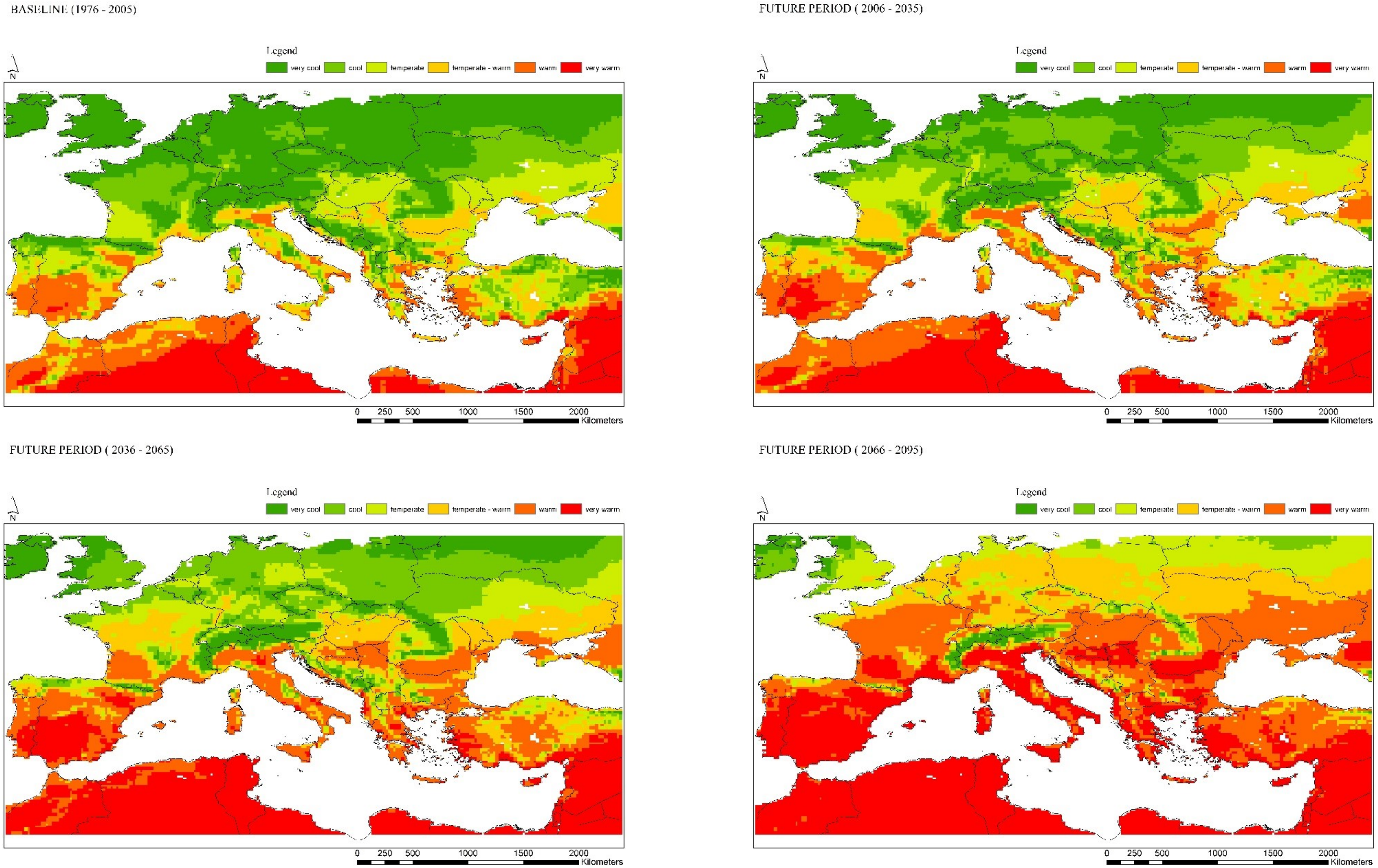

BASELINE (1976 - 2005)

FUTURE PERIOD (2006 - 2035)

FUTURE PERIOD (2036 - 2065)

FUTURE PERIOD (2066 - 2095)

Figure 2.14: HI index maps - comparison between BASELINE and RCP 4.5 scenarios



BASELINE (1976 - 2005)

FUTURE PERIOD (2006 - 2035)

FUTURE PERIOD (2036 - 2065)

FUTURE PERIOD (2066 - 2095)

Figure 2.15: HI index maps - comparison between BASELINE and RCP 8.5 scenarios

Grapevine suitability map

The grapevine suitability maps have been obtained by combining the soil suitability map (Fig. 2. 3), the DI-CI suitability maps (Fig. 2. 11, 2. 12) and the HI maps (Fig. 2. 14, 2. 15). Each map is the result of the overlay of the different variables for each period of analysis.

With regard to the baseline map (Fig. 2. 16), the areas coloured from red shades to yellow correspond to S1 classes, the green shades to S2 classes and the blue shades to S3 classes, while the areas not suitable for grapevine growth are shown in grey.

These suitable areas are in accordance to Schultz and Jones (2010) (§Introduction Fig. 1. 5) who show the presence of grapevine zones in the Mediterranean basin, and with the Corine Land-Cover classification map for the vineyard at European scale (Fig. 2. 17).

In this land suitability classification it is possible to distinguish the S1 area mainly concentrated in the Iberian Peninsula, in the south of France, in Italy and in Greece. In these areas, in fact, many late varieties such as Grenache and Syrah are widely spread while the international varieties, such as Merlot and Cabernet Franc, are also cultivated. Along the coastal areas it is possible to identify suitable areas for late varieties, able to grow in stress conditions.

The second suitable class (S2) includes the areas in which the grapevine grows, but with some limiting factors attributable to soil properties or night cooling. Similarly, S3 classes involve all the areas where grape cultivation is possible only with the adoption of particular techniques in order to limit the plants' imbalances as indicated also in Fraga et al (2015) and the references therein.

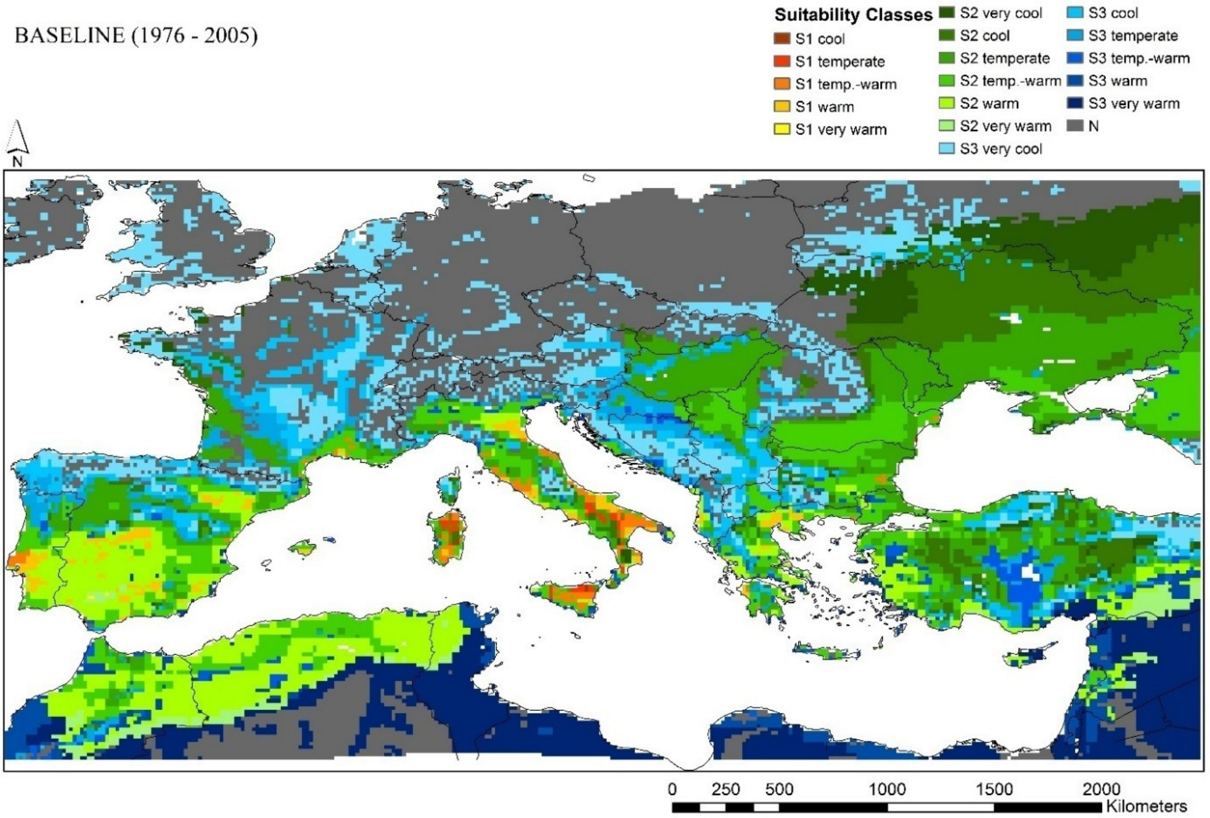


Figure 2.16: Grapevine suitability map - mean of historical period (1976-2005)

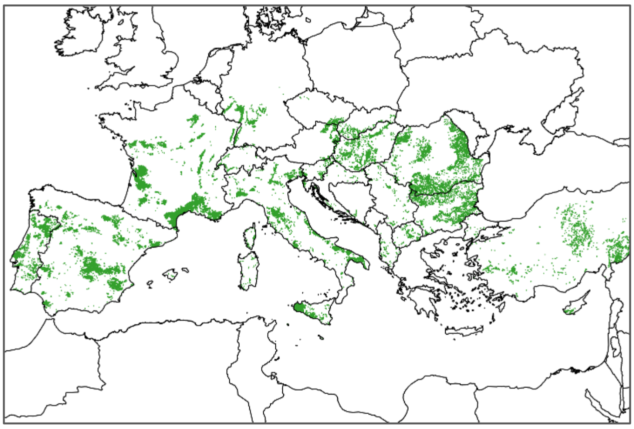
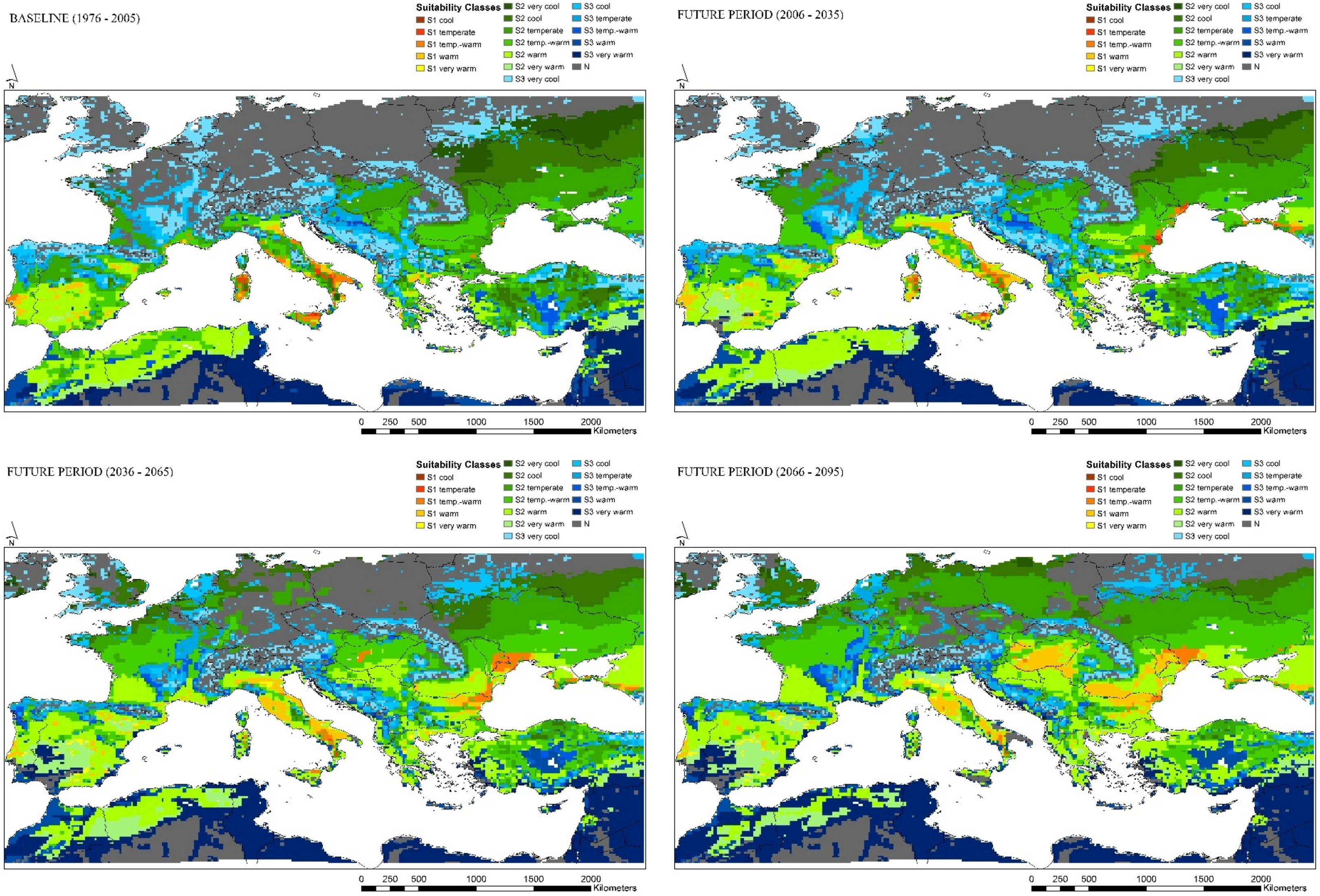


Figure 2.17: Corine Land Cover (2006) classification for vineyard

Future projections show a general decrease of the suitability area in the south of Europe, likely because of the high dryness both in soil and in climate variables. On the other hand, the eastern part of Europe might benefit from the effects of climate change. In these scenarios it is plausible to expect a detrimental impact on wine yield and quality parameters in the south while, conversely, new areas for viticulture and high quality wines may characterise the northeast of Europe (Figures 2.18, 2.19).


BASELINE (1976 - 2005)

FUTURE PERIOD (2006 - 2035)

FUTURE PERIOD (2036 - 2065)

FUTURE PERIOD (2066 - 2095)

Figure 2.18: Grapevine suitability map- comparison between BASELINE and RCP 4.5 scenarios

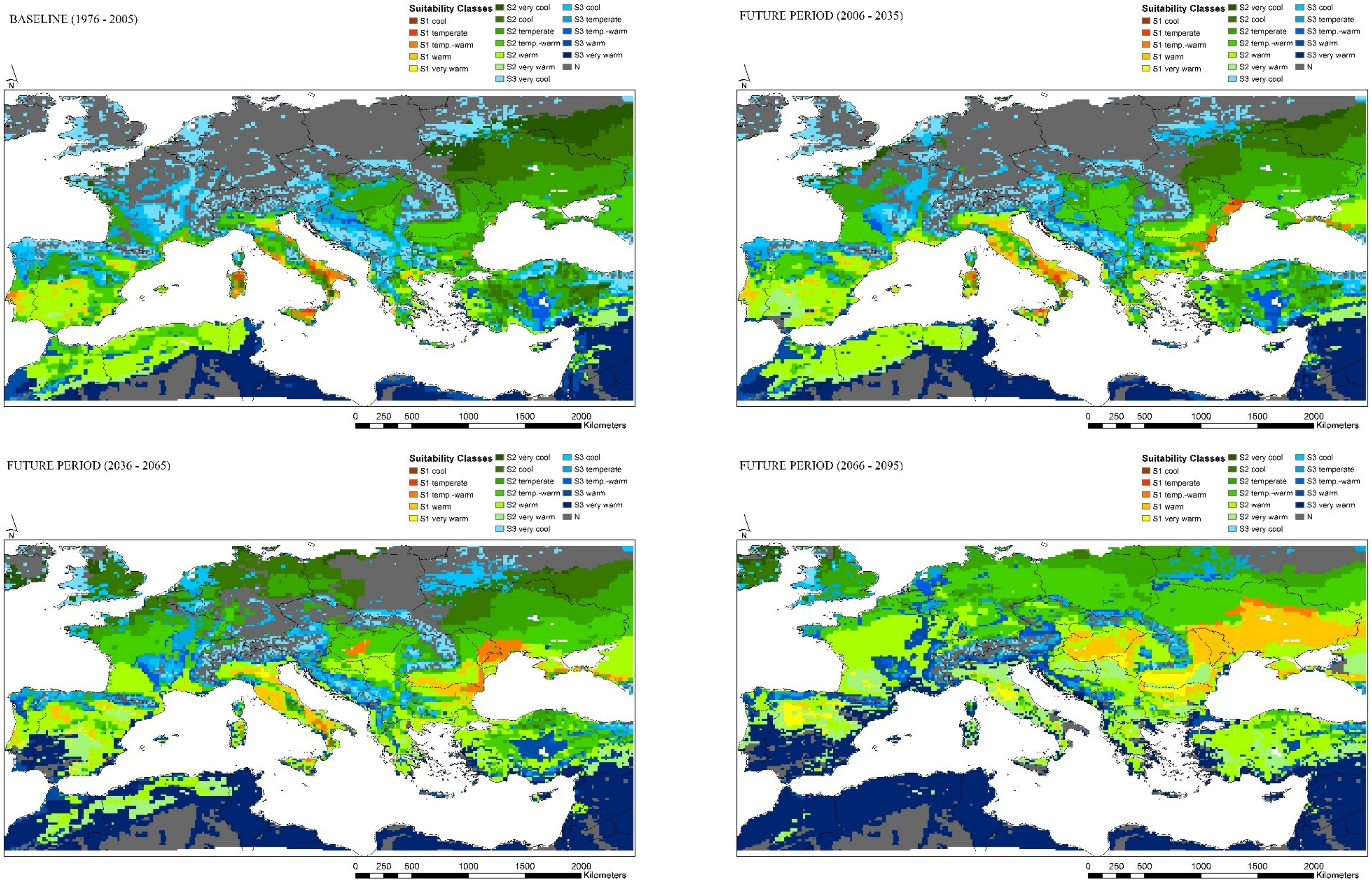


Figure 2.19: Grapevine suitability map - comparison between BASELINE and RCP 8.5 scenarios

In the different scenarios it is possible to see the increase of temperate-warm and warm classes around the sea basins; conversely, the cool and very cool area is projected to drastically decrease up to the European northern boundaries for S1 and S2 classes and in correspondence of mountain chains in S3.

The results presented here are also confirmed by previous studies (Fraga et al., 2015; Malheiro et al., 2010; Jones et al. 2005b, Stock et al., 2005) where the possibility to extend the grapevine cultivation until the regions currently too cold for this crop were sustained.

In comparison with current viticulture areas, the zones situated in the centre and west Europe can take advantage from future climate conditions, whereas on the regions located in southern Europe such future conditions might cause detrimental impacts.

In addition, the northern regions may increase the range of wine varieties as a result of climate change. Actually, in some German winegrowing regions, Stock et al. (2005) observed a process of change from white to red in some varieties because of more heat demand.

Fraga et al. (2015) cited also different studies where the main goal is the selection of international varieties with high thermal demand, in order to replace current varieties.

Conclusions

This study has calculated and analysed three different bioclimatic indices and two soil variables in order to assess the grapevine suitable areas under present climate conditions and projected climate change scenarios.

First the bioclimatic maps and subsequently the grapevine suitability maps, have shown an evident northward transition of the areas designated for grapevine cultivation. Among others, the late varieties might have an interesting role in the European zoning of the future.

The results obtained confirm the outcomes of other studies conducted in the same areas, however this study has additionally underlined the differences of thermal requirements of grape varieties.

However, the high resolution of climate data and the latest GHG emissions scenarios (RCP 4.5 and RCP 8.5), provide an added value at the results. In addition, in light of the fact that such added information may increase knowledge in terms of methodology of viticultural zoning studies while at a wide scale it may influence adaptations and mitigations strategies in order to choose the most suitable varieties for such areas.

Chapter 3: Grapevine phenological stages under climate change scenarios in a Mediterranean area - a modelling approach

Introduction

Climate change projections for the 21st century have been estimated to have important effects in terms of changes in temperature and precipitation patterns (Meehl et al. 2007), which may significantly vary the current viticultural zoning in Europe (Malheiro et al. 2010). Recent studies in Portugal (Fraga et al. 2012), and in Alsace, France (Duchene and Schneider, 2005), have indicated an increase in the growing-season temperature. In the same area and in the United States, Australia and Spain, Jones at al. (2005) have observed an increase of mean temperature in the dormancy period too.

In order to understand the consequence of these modifications on grape phenology, the climate change effects on phenological phase's expressions have been studied diffusely in the last years. In France, in the Gironda viticultural area, an advance of the phenological phases of Merlot and Cabernet Sauvignon varieties has been registered starting 1990 (Bois, 2007). Similarly, in Catalogna, Saladié et al. (2007) observed an advance of the harvest start date of the Macabeo variety during the period 1971-2006 and that this is correlated with an increase of minimum and maximum temperature during the growing period, between April and August. Rochard et al. (2006) have estimated that the grapes were harvested with an advance of a month in France in the last 50 years; and, more in general, in Europe 17 days before (Jones et al., 2005).

With regard to forthcoming viticulture, some simulations of possible scenarios have been carried out in recent years with the support of mathematical models, assuming different levels of thermal increase.

Jones (2007) asserts that climate change could significantly change the distribution of vines in the wine-growing areas. For this reason, the average temperature of the growing season is used to define the potential of ripening of grapes to produce wines with quality, and, accordingly, distinguishing cool, intermediate, temperate and warm areas. Thus, thermal increase may contribute to shift a viticultural region over the maximum thermal limit, under which the quality of wine is safeguarded. García de Cortázar et al., (2006), adopt a crop modelling approach to evaluate the impact of climate change on grape in two different areas in France. In this study, a reduction of the entire growth cycle is expected, with the exception of the dormancy phase. In García de Cortázar (2009), an advance of bud break phase with a consequent risk of frost damages is predicted in the vitivinicultural areas of the north of the France during the vegetation-growing period.

In Italy, Moriondo and Bindi (2005, 2007), have underlined the link between the potential increase of temperature due to the different climate scenarios, and the anticipation of bud break and harvest phases causing a substantial reduction of the whole growth cycle.

Webb et al. (2007) have predicted a reduction of 37 days of the growing season in Coonawarra (Australia) region, in 2050; similarly, in Spain, Ramos et al. (2008) have calculated an advance of 4.1 day every °C of increment between the minimum temperatures in respect to the present mean temperature of the veraison of Parellada variety.

Furthermore, the increase of temperature is conditioned by other climate components and their frequency, such as heat waves, drought period, and cloudburst, (Easterling et al., 2000, Brunetti et al. 2002, Klein Tank and Können 2003, Bartolini et al. 2008).

As a consequence of climate changes, it is probable that varieties currently planted will not be apt to reach the end of cycle growth under the same conditions in the future. Then, understanding how temperature influences the timing of V. vinifera L., both in vegetative and reproductive development phases, is decisive (Parker, 2011). For that reason, many phenological models were developed.

Phenological models used in agro meteorology allow simulating the development cycle of different crops, starting from climatic and meteorological information. As regards the budburst date, the models simulate the dynamics of the buds according to the trend of chilling temperature, a start period with low temperature, and, after that, the forcing temperature, a period during which the heat requirement is satisfied (Spanna et al., 2005).

Most studies of vine dormancy are old and were realized under controlled conditions (Pouget, 1963; Nigond, 1967). In that situation, Pouget (1967) and Bernstein (1984) presented the importance of exposure of the buds to low temperatures, below 10ºC, during a certain period and its relation on the rate of dormancy breaking and budburst. Thus, various authors define the response to temperature for orchard trees as "Cold Actions", (Bidabe, 1965a, b) or "Chilling requirements" (Richardson et al., 1974; Chuine, 2000; De Melo-Abreu et al., 2004; Cesaraccio et al., 2004).

Nevertheless several authors have developed methods for calculating the date of budburst of the vine without taking into account the dormancy phase. (McIntyre et al.,1982; Williams et al., 1985a,b; Moncur et al., 1989; Oliveira, 1998, Pouget, 1968; Riou, 1994). The calculations begin on January 1st (Gutierrez et al., 1985; Moncur et al., 1989; Riou, 1994; Bindi et al., 1997a, b; Oliveira, 1998; Brisson et al., 2002b), or after this date (Williams et al., 1985a, b), implicitly assuming that dormancy has already broken by this date and that the preceding pre-dormancy period has no bearing on the calculation.

Other models developed for orchard crops, take into account the dormancy to predict the flowering date and budburst (Bidabe, 1965 a, b; Richardson et al., 1974; Chuine, 2000), but require a huge amount of parameters.

To simulate the grapevine dormancy García de Cortázar-Atauri et al., (2006) have developed the BRIN model. Such model is able to evaluate the thermal requirement in the post-dormancy phase and the chilling requirement necessary to the budburst.

In relation to the simulation of grapevine development rate and phenology, several authors have contributed with different models: Bindi et al. (1997a; 1997b) presented a simple model allow to describe the development, growth and yield of grapevine according to ontogeny, leaf development, biomass accumulation and fruit growth processes in Chianti area (Tuscany – Italy). Caffarra and Eccel, (2010) tested three different phenological model (linear regression model; process-based model; Winkler degrees) on four main phases (Endodormancy, budburst-flowering; flowering-veraison; veraison-harvest) of Chardonnay variety in Veneto region. Parker et al. (2013, 2011) developed a general phenological model to characterise the timing of flowering and veraison for the grapevine at species level.

In general, the response of grapevine to temperature variation is represented by linear or non-linear heat summations (Gladstones, 1992). The linear models use a sum of temperatures above a base temperature corresponding to a fixed day of the year that is useful to predict the appearance of the next phenological stage (Hall and Jones, 2010). On the other hand, the non-linear models take into account a temperature threshold, optimal temperature, above and below which plant development is limited (Fig.3.1) (García de Cortázar-Atauri et al., 2010).

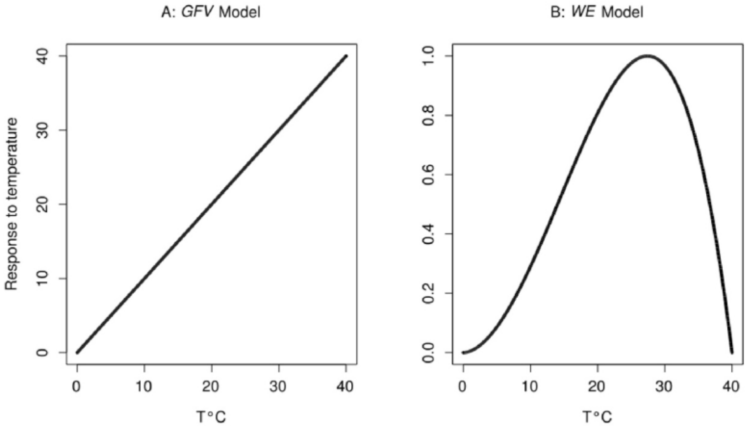


Figure 3.1. Daily response of plant development to temperature between 0 and 40 °C for the linear Grapevine Flowering Veraison (A) and curvilinear Wang and Engel (B) models.(Cuccia et al.2014)

Therefore, the estimation of the date of a phenological stage with the climate projections may differ depending on to the kind phenological model applied, if it is a linear or non-linear model In this part, the objective is to test different phenological model to represent the growth life cycle of grape, dormancy and development phases, on several varieties in Italy. The models were chosen considering the importance of including the dormancy phase in the simulation and the degree of model complexity according to linear and curvilinear approach. After that, the most performant model for each variety was used to simulate the impact due to the climatic change according to different climate scenarios.

Materials and Methods

Modelling approach

The Phenological Modelling Platform software version 5.5 (hereinafter called PMP5.5), designed by Chuine et al. (2013), was used to compare different phenological models. PMP5.5 is a man-machine interface for the Windows environment only, a user-friendly tool in which it is possible to create a phenological model, fit a phenological model to available data, or make simulations using an existing phenological model.

PMP5.5 allows the selection of a phenological model in a library and fitting the model to available data, or defining a new model thanks to the functions supplied with the software. By this way, in PMP5.5 it is possible to create an infinity of models. Each model is defined by a number of phenological phases that delineates it, the environmental variables that induce each phase, the response functions of the plant development to these variables, and the mode in which the phases are related.

Regarding the dormancy phase, this study uses the BRIN model proposed by García de Cortázar-Atauri et al., (2006), in which two sub-model were combined:

The Bidabe model (Bidabe, 1965a, b) that calculates the sum of Cold Action (CA) temperatures between the 1st of August and the dormancy break

$$f_{Bidabe}(Td)=Q10^{-Tmin}+Q10^{-Tmax}$$

Where daily minimum (T_{min}) and maximum (T_{max}) temperatures are the exponent of Q10 parameter that can accept value between 0 and 5. This study has adopted Q10=2.17 in accordance to the BRIN model,

The Richardson model (Richardson et al., 1974) that calculates the sum of the Growing Degree Hours (GDH) between the dormancy break, previously determined, and the bud break phase. Such model considers a range of efficient temperature between 5 (T_{low}) and 25 (T_{high}) °C

$$f_{Richardson}(T_d)=Max(Min(T_d-T_{low},\ T_{high}-T_{low}),0)$$

In the PMP5.5 library, two main phenological models were chosen to represent the grape cycle:

GDD (Growing Degree Day): the mostly used function to describe the phenology of species; it is a Thermal Time model based on Degree Day accumulation, is calculated as the difference between the mean day temperature (*Tm*) and the base temperature (*Tb*), below of which the development is null.

$$\begin{cases} GDD = (Tm - Tb) & if\ Tm > Tb \\ GDD = 0 & if\ Tm \leq Tb \end{cases}$$

Wang & Engel: this is a phenological model, based on the NHH (Normal Heat Hours) approach that takes into account three cardinal temperatures: minimum cardinal (T_{min}), optimal (T_{opt}) and maximum cardinal (T_{max}) temperatures. The minimum and maximum temperatures are two threshold temperature values below and above which no action on the plant is considered.

$$\begin{cases} \dfrac{2(T - Tmin)^{\alpha}(Topt - Tmin)^{\alpha} - (T - Tmin)^{2\alpha}}{(Topt - Tmin)^{2\alpha}} & if\ Tmin \leq T\ \leq Tmax \\ 0 & if\ T < Tmin\ or\ T\ > Tmax \end{cases}$$

In particular, different phenological models to simulate the annual growth cycle of grapevines were compared starting on the 1st of January. In accordance to available bibliographical information, this study uses the following: GDD without any restriction about temperature (Franco, 2014), GDD with a base temperature of 4°C (Franco, 2014), GDD with a base temperature of 7°C (Franco, 2014), GDD with a base temperature of 10°C (Garcia de Cortazar-Atauri, 2006), Wang&Engel with a minimum temperature at 7°C and a maximum at 35°C (WANG735) (Caterisano, et al., 2010), Wang&Engel with a minimum temperature at 0°C and a maximum at 40°C (WANG040) (Cuccia, et al., 2014) (Tab.3.1).

Table 3.1: phenological models considered (C.b.M.: Calculated by model)

Models	*Tb*	*Tmin*	*Tmax*	*Topt*
GDD	C.b.M			
GDD4	4°C			
GDD7	7°C			
GDD10	10°C			
WE735		7°C	35°C	C.b.M
WE040		0°C	40°C	C.b.M

Datasets

Phenological Dataset

This study has used different phenological grapevine datasets, thanks to which it has been possible to collect data for twelve grape varieties from twenty sites on Italian region. (Fig.3.2 and Tab. 3.1 Annex I)

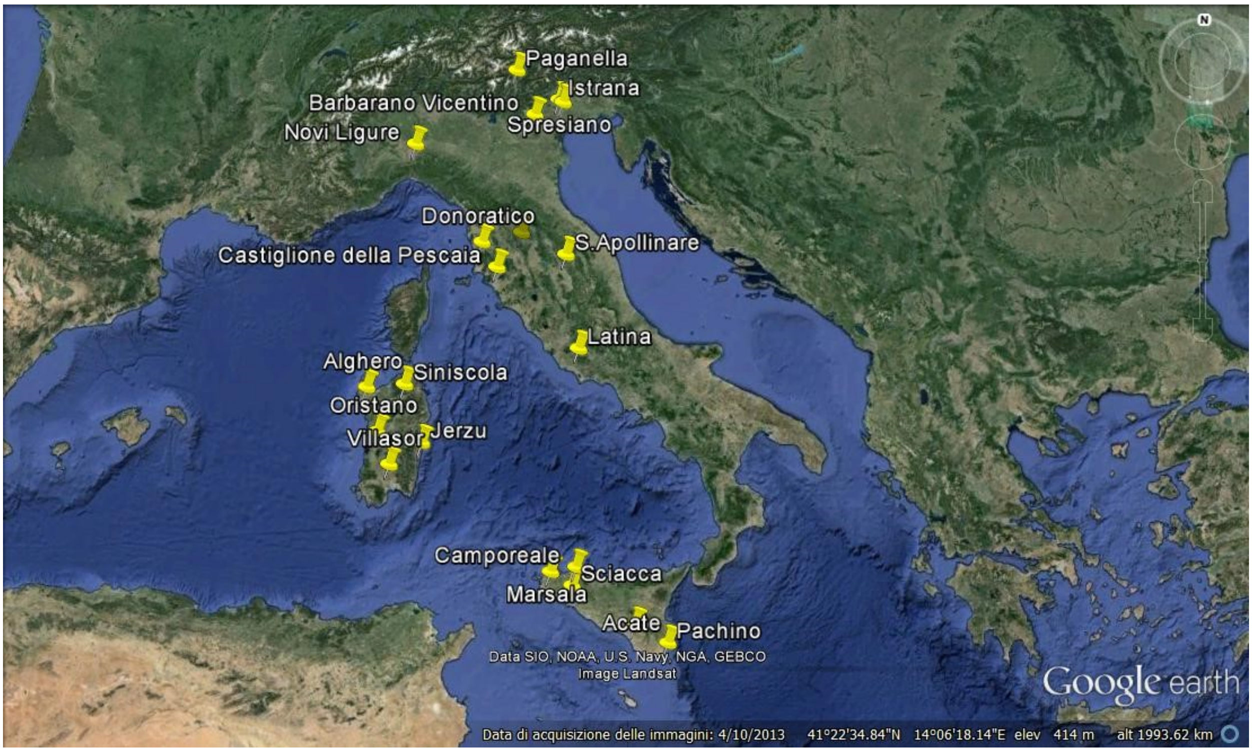


Figure 3.2 Sites where the phenological grapevine data were collected

The first set of data, available online at the URL http://phenagri.entecra.it/, is part of the project "Phenagri: phenology for agriculture" funded by the Ministry of Agriculture and Forestry (MiPAF) in the early '90s. The aims of the project were the monitoring of the state of the art knowledge in Italy on the phenology of many agricultural species and some weeds, to set new standards of observation and study of plants and their pests, and to promote a more effective organization and use of phenological data through the study of the relationship between weather patterns and seasonal evolution of the different species. Regarding this database, only the grape wine part has been taken into account, particularly the varieties of Cabernet Franc, Cabernet Sauvignon, Cannonau, Chardonnay, Merlot, White Pinot, Renan Riesling, Sangiovese, Sauvignon, and Vermentino (Tab. 3.2 Annex I).

The second section of dataset consists of two zoning studies, the first about the Cannonau grape wine in Sardinia Island, and the second about Tai (synonym of Cannonau, according to O.I.V.), Cabernet Sauvignon and White Pinot. (Tab. 3.3 Annex I)

A third part, concerning Cabernet Sauvignon, Nero d'Avola, Prosecco and Sangiovese was collected thanks to CARBOTREES PRIN project partners. In particular, the Cabernet Sauvignon varieties data were collected in "Castello di Brolio", "Donna Olimpia" and "Fattoria le Mortelle" farms by Consorzio Tuscania project. The Nero d'Avola data were collected by dott. A. Pisciotta at, among others, the "Azienda Agricola Planeta" farm. As regards Prosecco variety, the dataset was collect by dott. P.Belvini in "Belvini" farm (Tab 3.4 Annex I).

Data for Merlot variety were also considered from the information available on Pan European Phenology (PEP) website (http://www.pep725.eu/); PEP725 is a project with the goal to establish an open access database with plant phenology data sets for science, research and education (Tab 3.5 Annex I).

Other contributions on Cannonau and Vermentino varieties were found in Cossu, et al.(2004), Gometz (2005-2006), Porcu (2004-2005), and in a database of the Department of Science for Nature and Environmental Resources (DipNETex-Uniss-DESA), collected in precedent researches. (Tab 2.6 Annex I)

Meteorological data

The meteorological dataset was collected for each identified site and for the referenced period. To compensate for some missing data, the method proposed by Mancosu et al. (2014) was adopted. Details of each station are available in Annex I, table 3.7

Climate data

Our study considered two representative concentrations pathways (RCP) scenarios [RCP 4.5 (~500 ppm CO_2eq) and RCP 8.5 (~1370 ppm CO_2eq)], simulated with CMCC-MED model, with dynamic downscaling at 14 km, for the historical (1976-2005) and future scenarios (recent future 2006-2035; future 2036-2065; far future 2066-2095) (Bucchignani et al. 2014).

Statistical criteria

To obtain a single set of parameters valid over all the Italian territory, and so as to offset limitations of available database , this study uses cross validation for each variety, as proposed by Garcia de Cortázar-Atauri et al. (2009b).

This strategy allowed ignoring any possible regional peculiarities and analysing the dataset purely by cultivar.

PMP cross-validation process applied to each cultivar permits to have the result of each optimization algorithm in the form of statistical indices; thus, the following was produced:

SStot: Total sum of square of the data

$$SStot = \sum_{i=1}^{n} \left(Xobs_i - \overline{X}obs\right)^2$$

SSres: Residual sum of squares

$$SSres = \sum_{i=1}^{n} (Xobs_i - Xpre_i)^2$$

RMSE: Root mean squared error

$$RMSE = \sqrt{\frac{SSres}{n}}$$

EFF: Efficiency

$$EFF = \frac{(SStot - SSres)}{SStot}$$

Where:

Xobs: observed values of each phenological stage,

$\overline{X}$ obs: mean value of the observed dataset

Xpre: simulated values of each phenological stage,

n: the number of observations, used to fit the model

Methods

In the first part, the grape phenology in terms of dormancy phase and vegetative phase was analysed. For the dormancy phase, the BRIN model was adopted to evaluate the chilling requirement of different varieties; regarding the vegetative phase; in this part six different phenological models were paralleled to compare linear and beta model performances in order to study as best as possible the impacts of climatic change on grapevine.

Regarding the dormant phase, only the observations in which the meteorological dataset was as complete as possible were considered. Thus, in some cases not all the available phenological dataset was considered. Results for vegetative phase were obtained selecting the best-fitted model according to the minimum RMSE (< RMSE) after the cross-validation process.

In this section the different phenological models were performed using meteorological data observations according to table 3.7 in Annex I.

In the second part, the impact of climate change on each variety of grape using the phenological model performed in the previous part was analysed. In this section only the variety that had an RMSE less than 30 days for the entire cycle growth was simulated. Each variety was simulated in the sites of its respective study.

Phenological models analysis

The analysis on different models of phenological grapevine stages has allowed comparing different temperature thresholds for different varieties.

The BRIN model results have revealed a high variety of response of different grape cultivar (Tab.3.2).

Table 3.2: SStot (Total sum of square of the data), SSres (Residual sum of squares), RMSE (Root mean squared error), EFF (Efficiency) and number of observations (NbObs) for each variety, in relation to the BRIN model

	SStot	*SSres*	*RMSE*	*EFF*	*NbObs*
CABERNET FRANC	486.22	794.66	9.40	-0.63	9
CABERNET SAUVIGNON	2928.36	10401.81	27.26	-2.55	14
CANNONAU	4074.75	7783.00	14.70	-0.91	36
CHARDONNAY	680.88	750.45	9.69	-0.10	8
MERLOT	734.29	27070.68	35.90	-35.87	21
NERO D'AVOLA	2000.47	13028.56	27.68	-5.51	17
WHITE PINOT	761.00	1003.15	7.92	-0.32	16
PROSECCO	1218.12	134.79	2.82	0.89	17
RENAN RIESLING	795.56	1042.77	10.76	-0.31	9
SANGIOVESE	821.60	989.21	9.95	-0.20	10
SAUVIGNON	406.00	809.63	9.48	-0.99	9
VERMENTINO	3448.47	3881.57	15.11	-0.13	17

In table 3.2, it is possible to observe that the SStot assume value between 406.00, for the Sauvignon variety, and 4074.75, for Cannonau variety; as regard SSres, the minimum value is registered for Prosecco (134.79) and the maximum for Merlot varieties (27070.68).

Hence, RMSE assume different values according to the ratio SSres/n° observations, therefore the Prosecco variety shows the best performance with 2.82 days of error, while the Merlot variety shows the worst result with the highest RMSE (35.90).

Good value of RMSE was given by White Pinot (7.92), Cabernet Franc (9.40), Sauvignon (9.48), Chardonnay (9.69) and Sangiovese (9.95); elevated results as RMSE equal to 27.68 and 27.26 were obtained for Cabernet Sauvignon and Nero d'Avola, respectively. Intermediate values were indicated for Renan Riesling (RMSE= 10.76), Cannonau (RMSE=14.70) and Vermentino (RMSE=15.11) varieties. Similarly the efficiency index provides a similar information, with high performance for the Prosecco variety, the only one with a positive efficiency (0.89), and a negative efficiency value (-35.87) for the Merlot variety.

All other results reveal a negative efficiency value; Chardonnay (-0.10), Vermentino (-0.13), Sangiovese (-0.20), Renan Riesling (-0.31), White Pinot (-0.32), Cabernet Franc (-0.63), Cannonau (-0.91) and Sauvignon (-0.99) varieties included between 0 and -1; Cabernet Sauvignon with an EFF equal to -2.55 and Nero d'Avola with EFF equal to -5.51.

These results were in accordance with other studies conduct by di Lena (2011) and di Lena & Silvestroni (2009) in which Montepulciano and Sangiovese varieties displayed good performances in terms of RMSE values, between 10 and 5 days generally, but the EFF results were in all cases negative. Those results are partially explained by the fact that the efficiency expresses the portion of variation in the observation set accounted for the model. Regarding this study, the data observations are scattered on different areas according to the available dataset, and for that reason it is plausible that the efficiency cannot described the entire variability of the observations dataset.

As regards the representation of the grape cycle, six different models were compared, but only three of those gave back effective results.

The GDD model was effective for Cabernet Sauvignon (RMSE = 7.89), Cannonau (RMSE = 6.38), and Nero d'Avola (RMSE = 5.75) varieties; WANG735 was the best model for White Pinot (RMSE = 7.51), and WANG040 for all others, in which the RMSE is ever lesser than 8 days (Tab.3.3)

Table 3.3: Phenological models performance according to RMSE (Root Mean Square Error) value; in which GDD (Growing Degree Days), GDD4 model with Tb=4°C, GDD7 model with Tb=7°C, GDD10 model with Tb=10°C, WANG040 model is Wang&Engel model with Tmin=0°C and Tmax=40°C, WANG735 model is Wang&Engel model with Tmin=7°C and Tmax=35°C.

varieties	*nobs*	*models*					
		GDD	GDD4	GDD7	GDD10	WANG040	WANG735
CABERNET_F	56	7.49	8.80	8.57	8.29	5.34	7.96
CABERNET_S	80	7.89	9.07	9.21	9.73	8.18	8.86
CANNONAU	213	6.38	6.86	6.73	8.88	6.60	6.63
CHARDONNAY	58	5.92	6.80	6.63	8.20	5.19	6.41
MERLOT	94	10.79	14.04	17.03	25.31	6.07	11.03
NERO D'AVOLA	48	5.72	6.59	6.47	6.39	6.67	6.49
WHITE PINOT	78	9.15	9.62	9.68	10.42	8.94	7.51
PROSECCO	80	2.93	3.30	3.27	3.54	2.82	3.14
RENAN RIESLING	60	6.75	7.66	7.41	7.77	5.35	6.77
SANGIOVESE	72	7.53	7.99	8.28	9.30	6.67	8.26
SAUVIGNON	60	7.07	7.92	7.61	7.71	5.36	7.18
VERMENTINO	118	8.25	9.32	10.08	10.20	7.56	8.97

Similarly the efficency index provides the same result in terms of performance of the model (Tab.3.4). The best performance was achieved by the Prosecco variety, with 0.84, followed by Chardonnay (0.68), Renan Riesling (0.53) and Sauvignon (0.45); a positive efficiency is register for Sangiovese (0.28), Vermentino (0.21) and White Pinot (0.09) too. Unfortunately none of the models could perform well for the Merlot (-0.08) and the Cabernet Franc (-0.09) varieties

Table 3.4: Phenological models performance according to EFF (Efficiency) value; in which GDD (Growing Degree Days), GDD4 model with Tb=4°C, GDD7 model with Tb=7°C, GDD10 model with Tb=10°C, WANG040 model is Wang&Engel model with Tmin=0°C and Tmax=40°C, WANG735 model is Wang&Engel model with Tmin=7°C and Tmax=35°C

varieties	*nobs*	*models*					
		GDD	GDD4	GDD7	GDD10	WANG040	WANG735
CABERNET_F	56	-1.14	-1.92	-1.77	-1.59	-0.09	-1.39
CABERNET_S	80	0.16	-0.11	-0.14	-0.28	0.10	-0.06
CANNONAU	213	0.50	0.43	0.45	0.02	0.47	0.48
CHARDONNAY	58	0.59	0.45	0.38	0.13	0.68	0.42
MERLOT	94	-2.40	-4.75	-7.49	-17.02	-0.08	-2.56
NERO D'AVOLA	48	0.27	0.04	0.07	0.09	0.01	0.06
WHITE PINOT	78	-0.35	-0.49	-0.51	-0.75	-0.29	0.09
PROSECCO	80	0.83	0.78	0.78	0.75	0.84	0.80
RENAN RIESLING	60	0.21	-0.01	0.06	-0.04	0.53	0.21
SANGIOVESE	72	0.08	-0.05	-0.13	-0.43	0.28	-0.13
SAUVIGNON	60	0.12	-0.10	-0.01	-0.04	0.45	0.10
VERMENTINO	118	0.06	-0.20	-0.03	-0.06	0.21	-0.15

These results appear partially in accordance with Parker et al. (2011) and Cuccia et al. (2014) where the GDD10 model revealed bad performances for all varieties and for different dataset, while on the other hand the WANG040 model explained the major part of the variability of grapevine varieties. Also in Fila et. al (2014) the beta model provided best performances than linear model.

The critical temperatures proposed represent thresholds above which, for GDD models (Tb= 4°C; Tb=7°C; Tb=10°C), or between which, for Wang and Engel (7-35 °C; 0-40°C), the physiological processes acquire importance for phenological development. The results indicate two main considerations, firstly that the temperature beyond the thresholds measured may influence the phenological development as well as the temperature above or between them; and secondly that the threshold temperature considered may be optimal for model prediction but might not correspond automatically with the temperature threshold able to describe the physiological processes below the developmental stage.

Impact of climate change on grapevine varieties

In the second part of this section, the BRIN model was combined with the phenological growth development models to understand the grape behaviour in relation to the simulation of possible future global warming.

Here, this study has adopted only the models that performed well in the previous steps on the basis of the sum of the RMSE for the dormancy phase and the RMSE for the development phase (Tab. 3.5).

Table 3.5: Growth cycle grape model created by the association of dormancy and development models for each variety, and the sum of the RMSE for the two step models

variety	*Growth cycle grape model*	*RMSE*
CABERNET_F	BRIN+WANG040	14.73
CABERNET_S	BRIN+GDD	35.15
CANNONAU	BRIN+GDD	21.08
CHARDONNAY	BRIN+WANG040	14.88
MERLOT	BRIN+WANG040	41.98
NERO D'AVOLA	BRIN+GDD	33.40
WHITE PINOT	BRIN+WANG735	15.43
PROSECCO	BRIN+WANG040	5.63
RENAN RIESLING	BRIN+WANG040	16.12
SANGIOVESE	BRIN+WANG040	16.62
SAUVIGNON	BRIN+WANG040	14.85
VERMENTINO	BRIN+WANG040	22.67

Although the phenological-vegetative models have shown good results for RMSE in the major part of the varieties, the dormancy model contributed to increase the total RMSE, as reported in table 3.5. Then, it was assumed that an RMSE higher than a month (30 days) is not satisfactory for the subsequent climate change simulations. This time range, in effect, is the physiological time when the different phenological phases may appear from north to south of Italy, as illustrated in the phenological bulletin of IPHEN project for Cabernet Sauvignon and

Chardonnay varieties. Thus, in accordance with the above considerations, such information was adopted for all varieties.

The varieties that were excluded due to a high RMSE value are Merlot, with a RMSE equal to 41.98, Cabernet Sauvignon with 35.15 of RMSE value and Nero d'Avola, with more than a month of error (33.40). Therefore, the varieties that were simulated are Cabernet Franc (14.73), Cannonau (21.08), Chardonnay (14.88), White Pinot (15.43), Prosecco (5.63), Renan Riesling (16.12), Sangiovese (16.62), Sauvignon (14.85) and Vermentino (22.67).

The simulation of the impact on grapevine under climate change conditions reveal a general shortening of the life growth cycle, in particular highlighting that the trend of the dormancy phase will increase during its own duration, whereas the bud break – veraison development period will decrease in length. (Graphs from 3.1 to 3.12).

However, this modification will be different for the single sites in different periods. Comparing the baseline scenario with three future scenarios (recent future 2006-2035; future 2036-2065; far future 2066-2095), in all cases, the RCP 8.5 scenario accentuates the information given by the RCP 4.5 (Tables from 3.6 to 3.15).

As regards the dormancy phase, the increase in its length is attributable to the high temperatures in winter periods that generate a delay at the end of this phase and, consequently, in the bud burst. (Jones et al. 2005)

On the contrary, the phase length between the end of the dormancy and the bud break will be drastically reduced; whereas the length of the bud break -flowering phase will be generally constant (about 45 days). The flowering - veraison phase for the different varieties in different sites reveals a general duration trend of about 70 days through the different periods.

The cycle will be reduced for all varieties, during the last period of simulation (2066-2095) according to the RCP 8.5. In particular, for the Cannonau variety, this reduction will amount to 30 days compared to the historical period. The least modification will be observed for White Pinot between the first future period (2006-2035) and the past period (1976-2005).

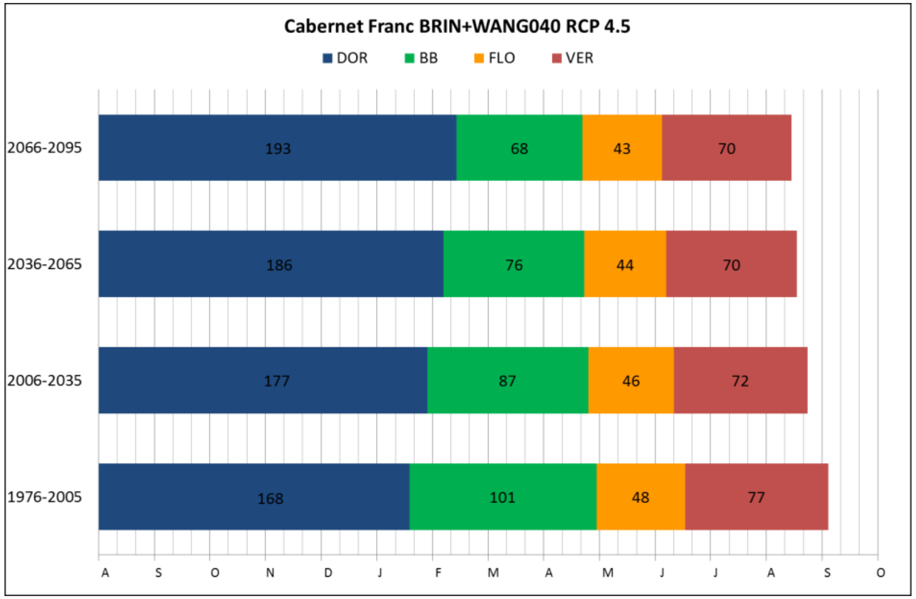
Regarding the single phenological phases, the highest value for dormancy was registered for Sauvignon variety in the last period of simulation (2066-2095), in RCP 8.5 conditions, with a duration of 68 days. The lowest value was registered in Cannonau variety for this historical period with only 2 days. The bud break has its minimum value in the last period of simulation (RCP 8.5) of the White Pinot variety (42 days) and the maximum for the Vermentino variety in the historical period (126 days). On the other hand, the flowering resulted less variable of the two preceding phases. In fact, the minimum value was 38 days for the Cabernet Franc in the thirty years 2066-2095, and 59 days for the Cannonau variety as maximum value. Nevertheless, the veraison displayed a maximum range of change in length duration of 10 days, particularly between the second (2036-2065) and the third (2066-2095) period of RCP 8.5 scenario for the Chardonnay variety.

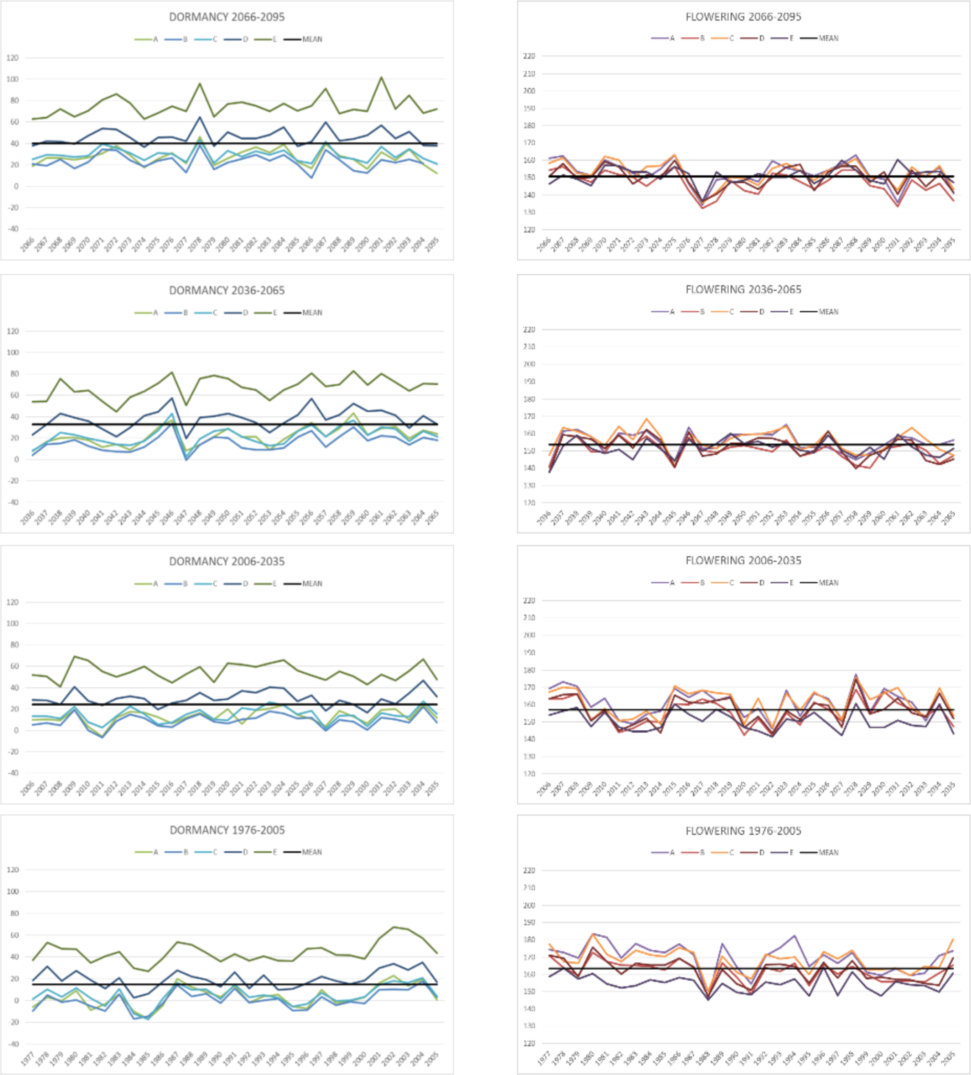
However, Merlot, Prosecco and Sangiovese did not provide the complete simulations in relation to the scenarios. This inconvenience suggest that the grapes phenology describes a very fragile balance for the plants and climate; in this case, even the model with the best performance is unable to really understand the plant dynamics.

The following graphs show the different answers to climate change effect under RCP 4.5 and RCP 8.5 scenarios for four different period (baseline 1976-2005, recent future period 2006-2035, future period 2036-2065, and the far future period 2066-2095). The results show the impact on each single variety as mean values of the thirty-year period, for each phase (1st August- end Dormancy; end-Dormancy- 50%Bud Break; 50%Bud Break – 50%Flowering; 50%Flowering – 50%Veraison), according to different sites in which the varieties were observed (Annex 1). In parallel, the graphs of dormancy (1st August- end Dormancy) and flowering (50%Flowering – 50%Veraison) phases show the behaviour of the cultivar in each site; the dormancy graphs were developed assuming the 1st of January as equal to 0.

Graph 3.1a simulations results of the impact of climate change on Cabernet Franc

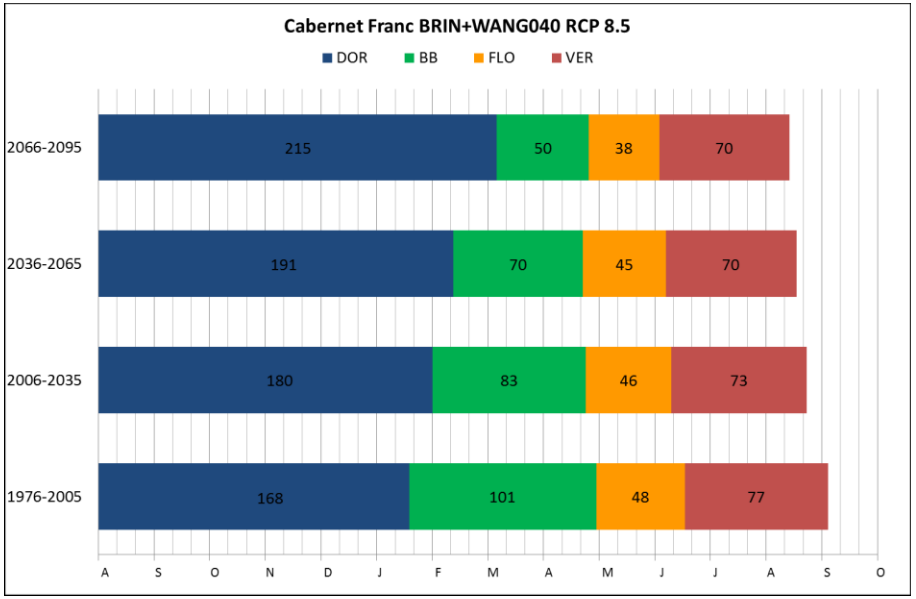
Graph 3.1b simulations results of Dormancy and Flowering phases through the different sites [A=Tenuta Cannona (AL); B=Spresiano (TV); C= S.Apollinare (PG); D= Latina; E=Villasor (CA)]

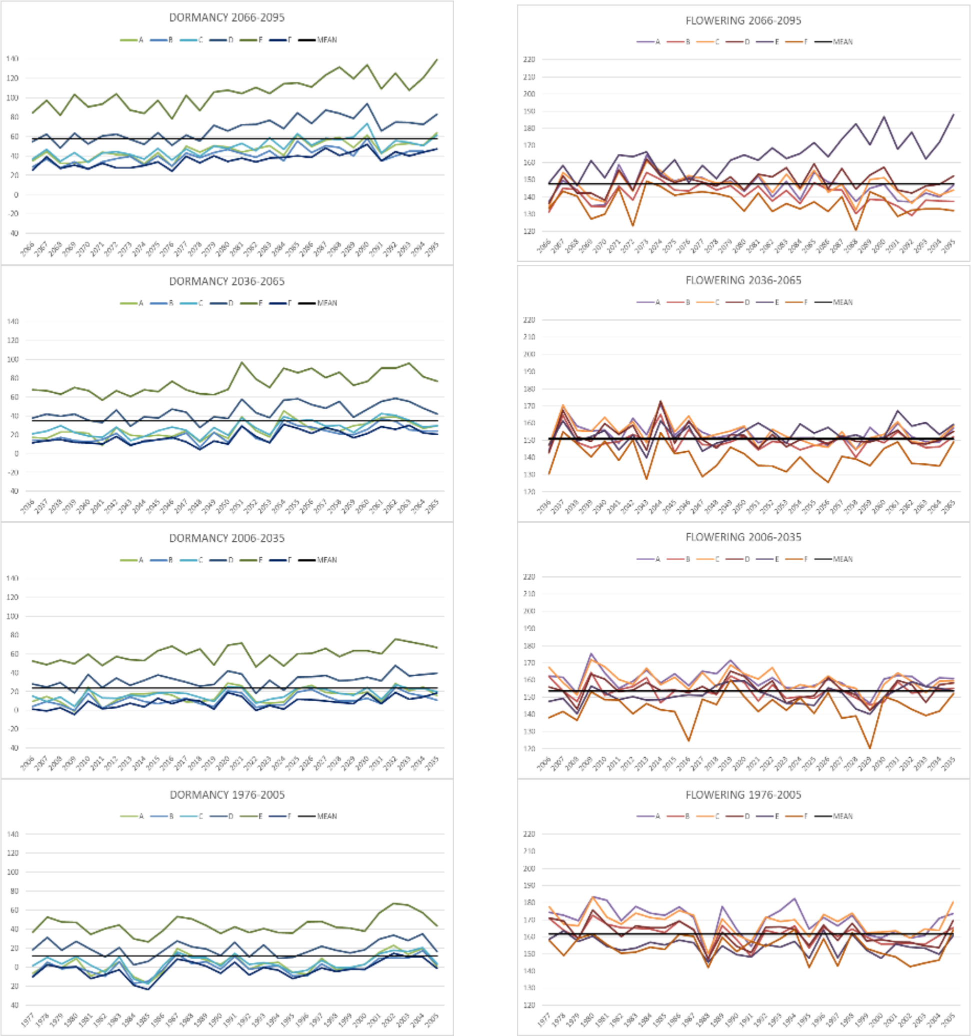




Graph 3.2a simulations results of the impact of climate change on Cabernet Franc

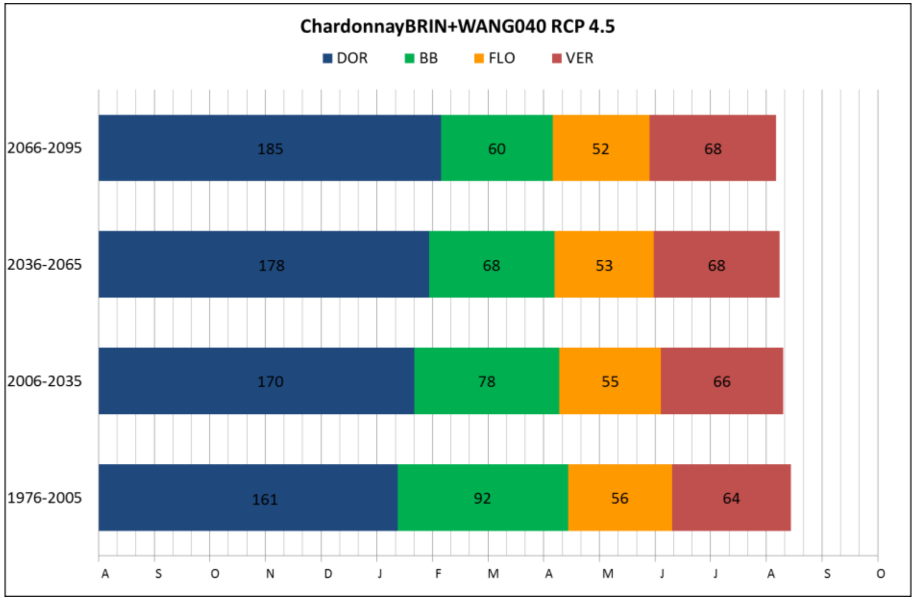
Graph 3.2b simulations results of Dormancy and Flowering phases through the different sites [A=Tenuta Cannona (AL); B=Spresiano (TV); C= S.Apollinare (PG); D= Latina; E=Villasor (CA)]

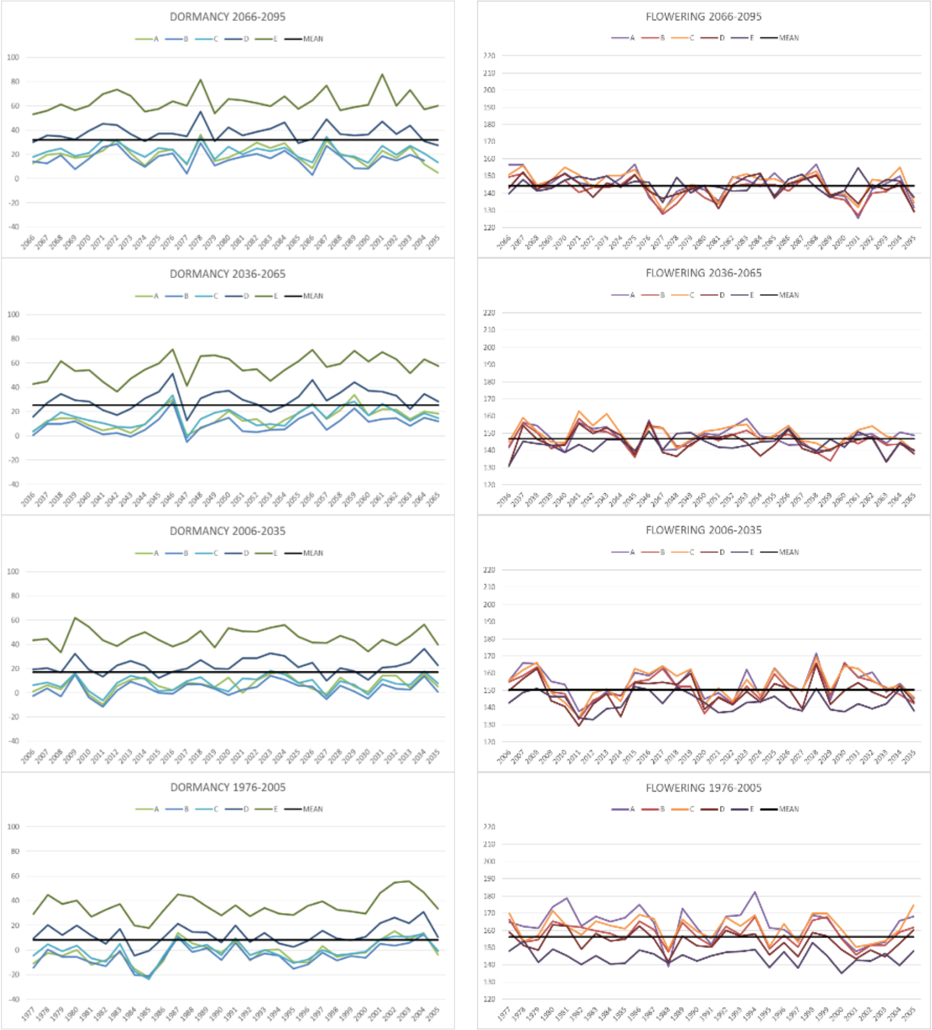




Graph 3.3a simulations results of the impact of climate change on Chardonnay

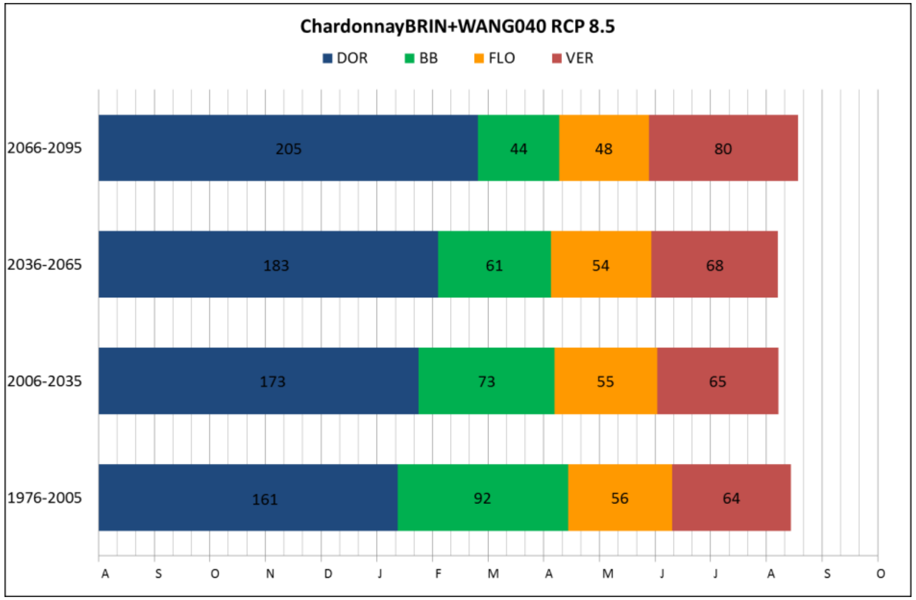
Graph 3.3b simulations results of Dormancy and Flowering phases through the different sites [A=Tenuta Cannona (AL); B=Spresiano (TV); C= S.Apollinare (PG); D= Latina; E=Villasor (CA)]

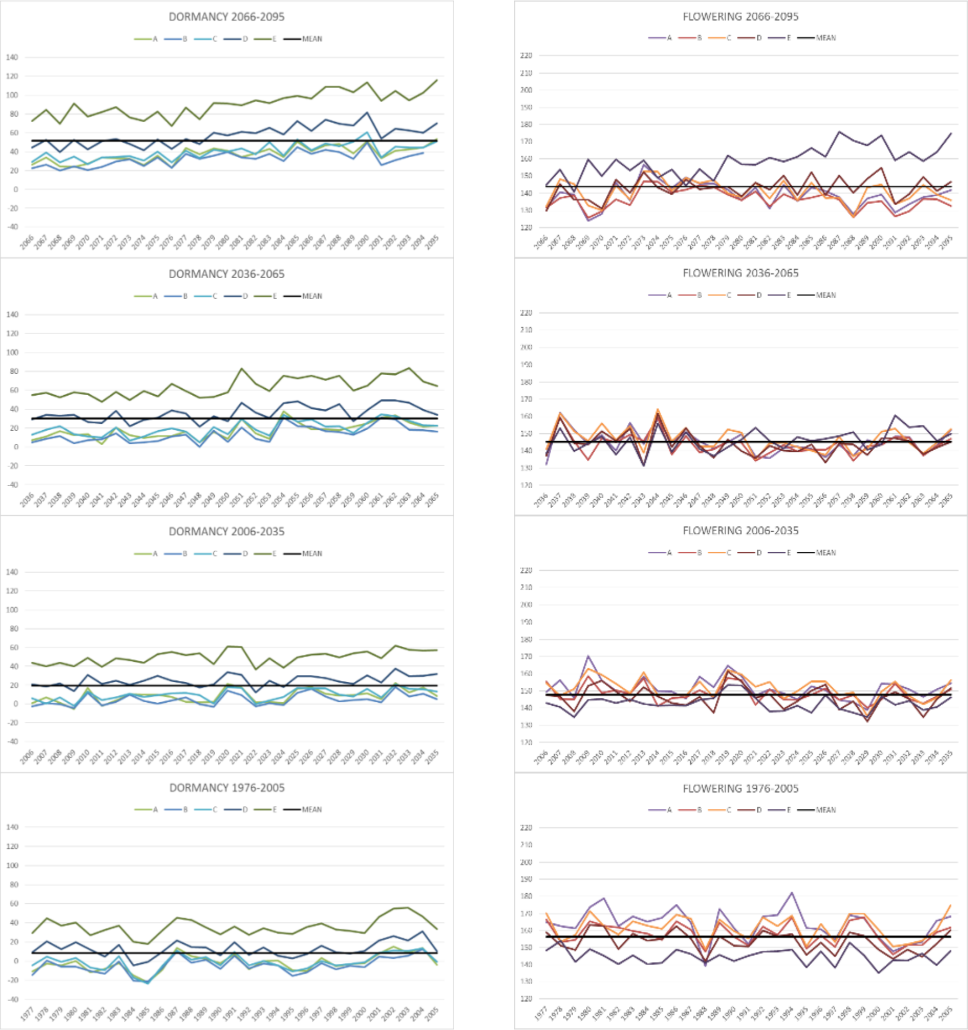




Graph 2.4a simulations results of the impact of climate change on Chardonnay

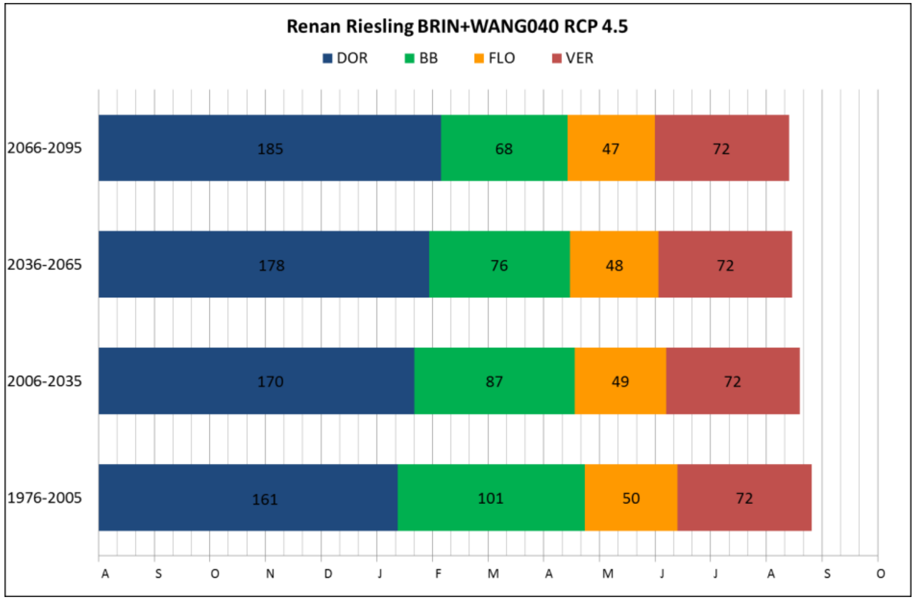
Graph 2.4b simulations results of Dormancy and Flowering phases through the different sites [A=Tenuta Cannona (AL); B=Spresiano (TV); C= S.Apollinare (PG); D= Latina; E=Villasor (CA)]





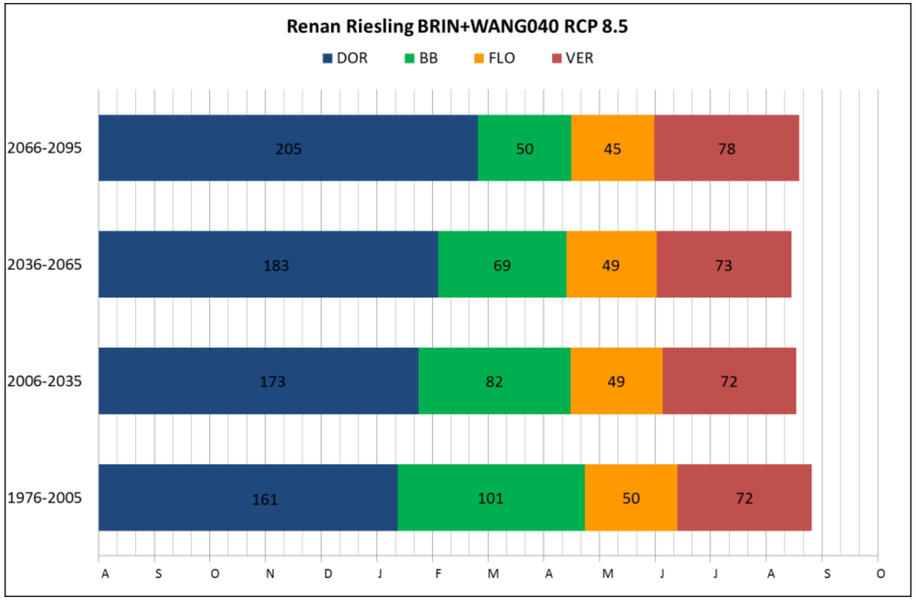
Graph 3.5a simulations results of the impact of climate change on Renan Riesling

Graph 3.5b simulations results of Dormancy and Flowering phases through the different sites [A=Tenuta Cannona (AL); B=Spresiano (TV); C= S.Apollinare (PG); D= Latina; E=Villasor (CA)]



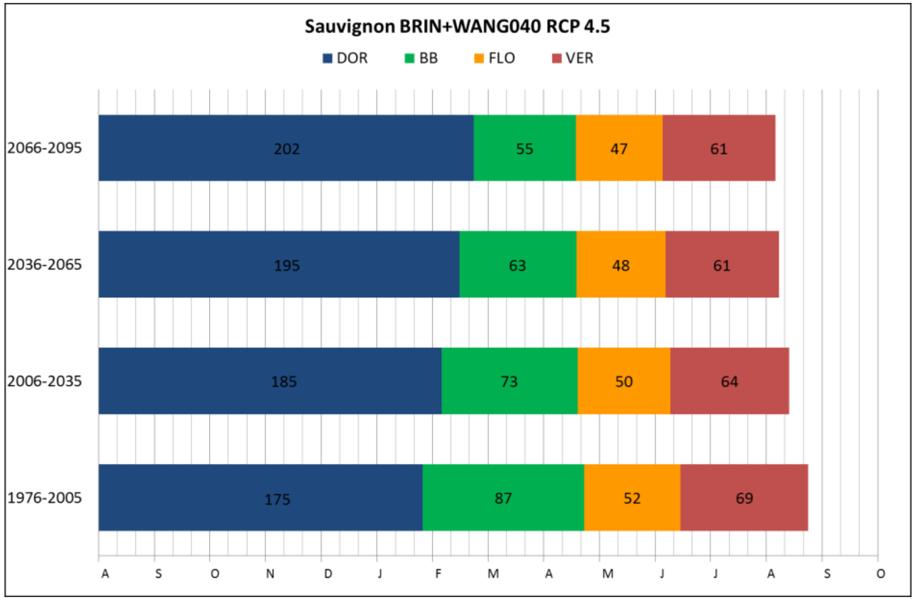
Graph 3.6a simulations results of the impact of climate change on Renan Riesling

Graph 3.6b simulations results of Dormancy and Flowering phases through the different sites [A=Tenuta Cannona (AL); B=Spresiano (TV); C= S.Apollinare (PG); D= Latina; E=Villasor (CA)]



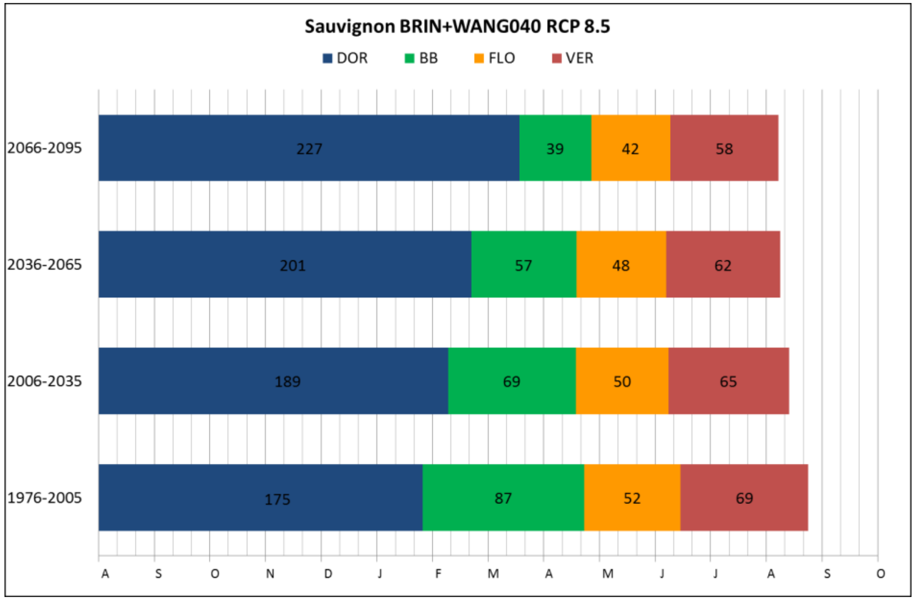
Graph 3.7a simulations results of the impact of climate change on Sauvignon

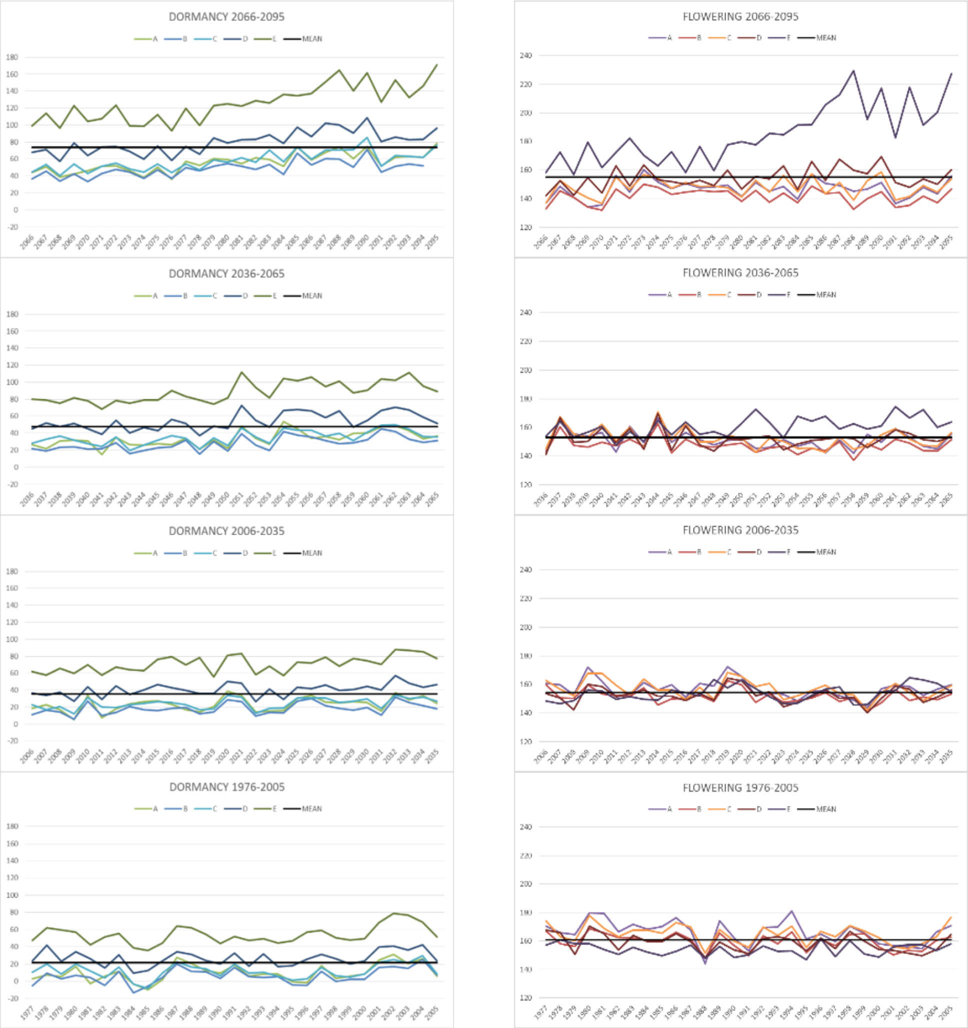
Graph 3.7b simulations results of Dormancy and Flowering phases through the different sites [A=Tenuta Cannona (AL); B=Spresiano (TV); C= S.Apollinare (PG); D= Latina; E=Villasor (CA)]



Graph 3.8a simulations results of the impact of climate change on Sauvignon

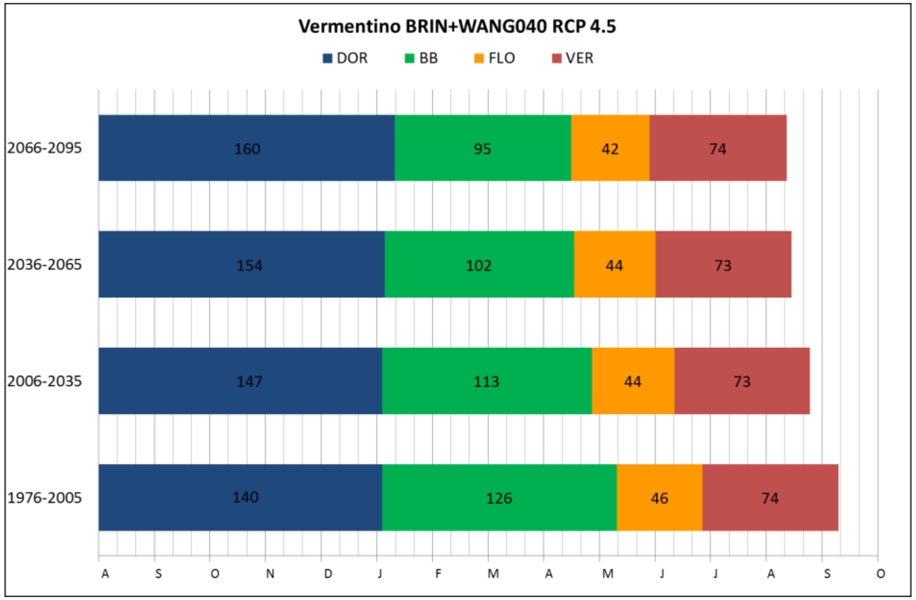
Graph 3.8b simulations results of Dormancy and Flowering phases through the different sites [A=Tenuta Cannona (AL); B=Spresiano (TV); C= S.Apollinare (PG); D= Latina; E=Villasor (CA)]

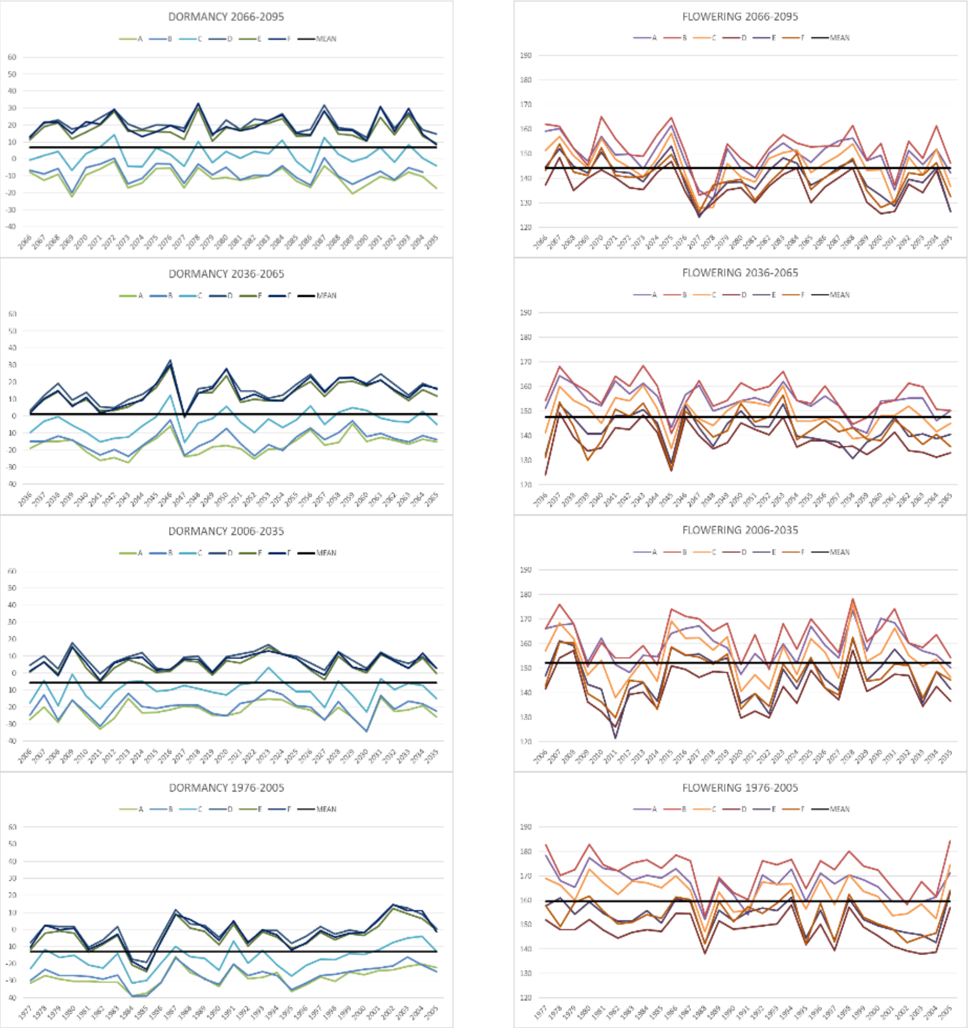




Graph 3.9a simulations results of the impact of climate change on Vermentino

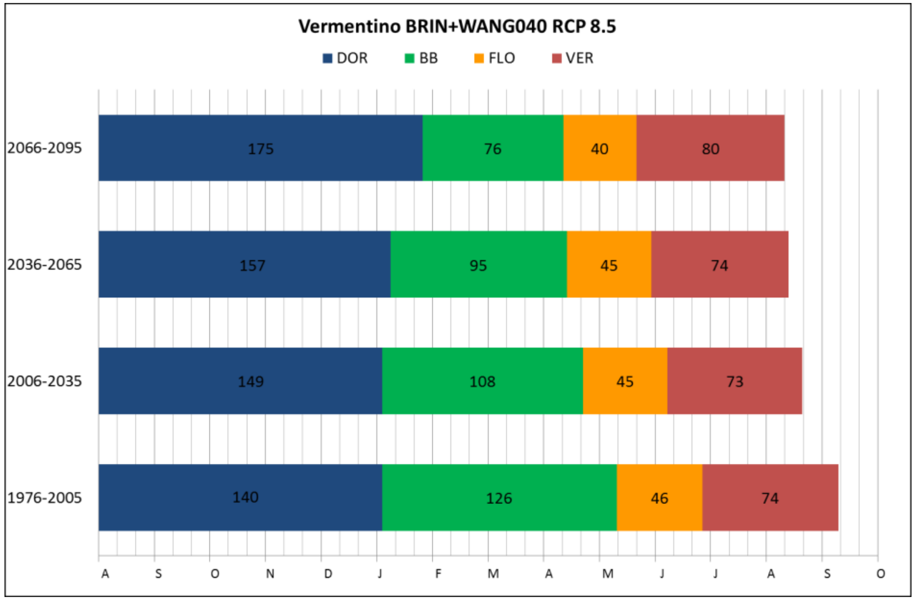
Graph 3.9b simulations results of Dormancy and Flowering phases through the different sites [A=Spresiano (TV); B= S.Apollinare (PG); C= Latina; D=Villasor (CA); E=Alghero (SS); F=Oristano (OR)]

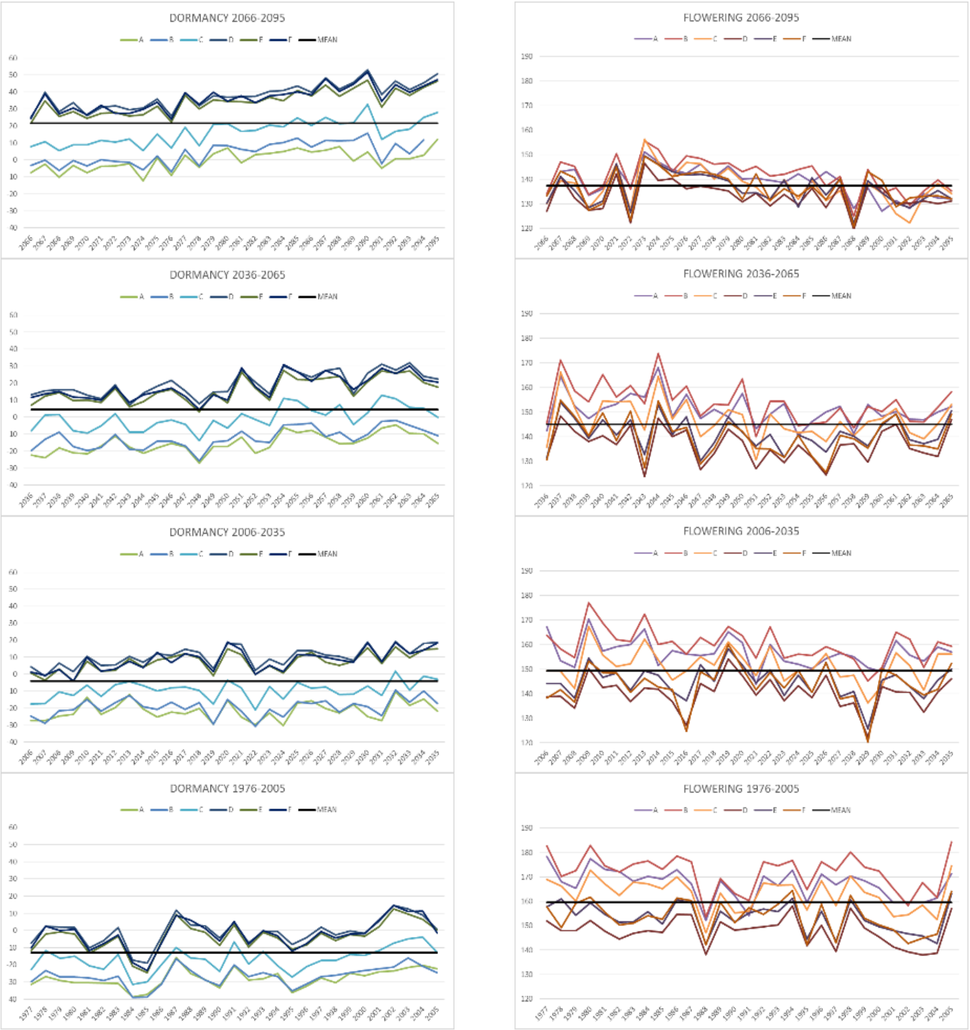




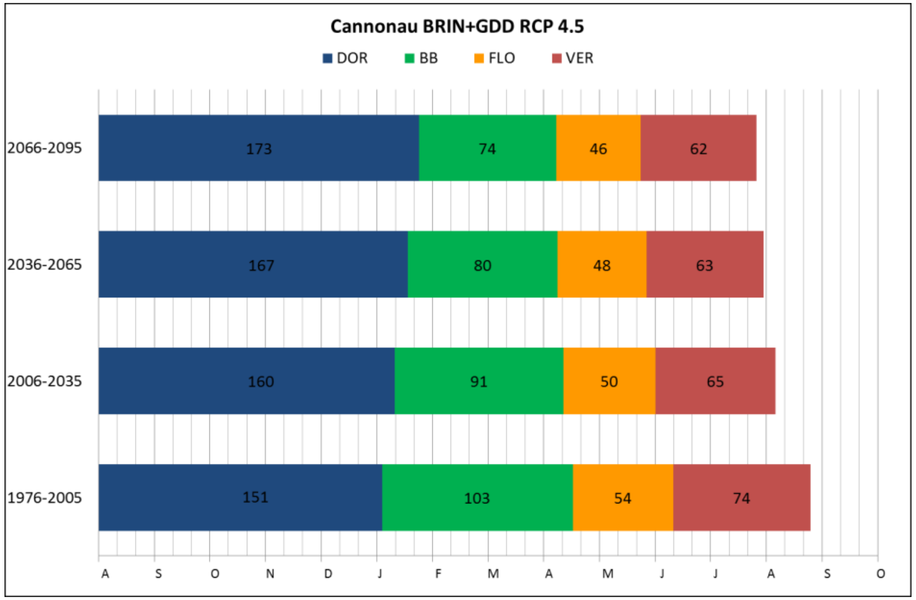
Graph 3.10a simulations results of the impact of climate change on Vermentino

Graph 3.10b simulations results of Dormancy and Flowering phases through the different sites [A=Spresiano (TV); B= S.Apollinare (PG); C= Latina; D=Villasor (CA); E=Alghero (SS); F=Oristano (OR)]

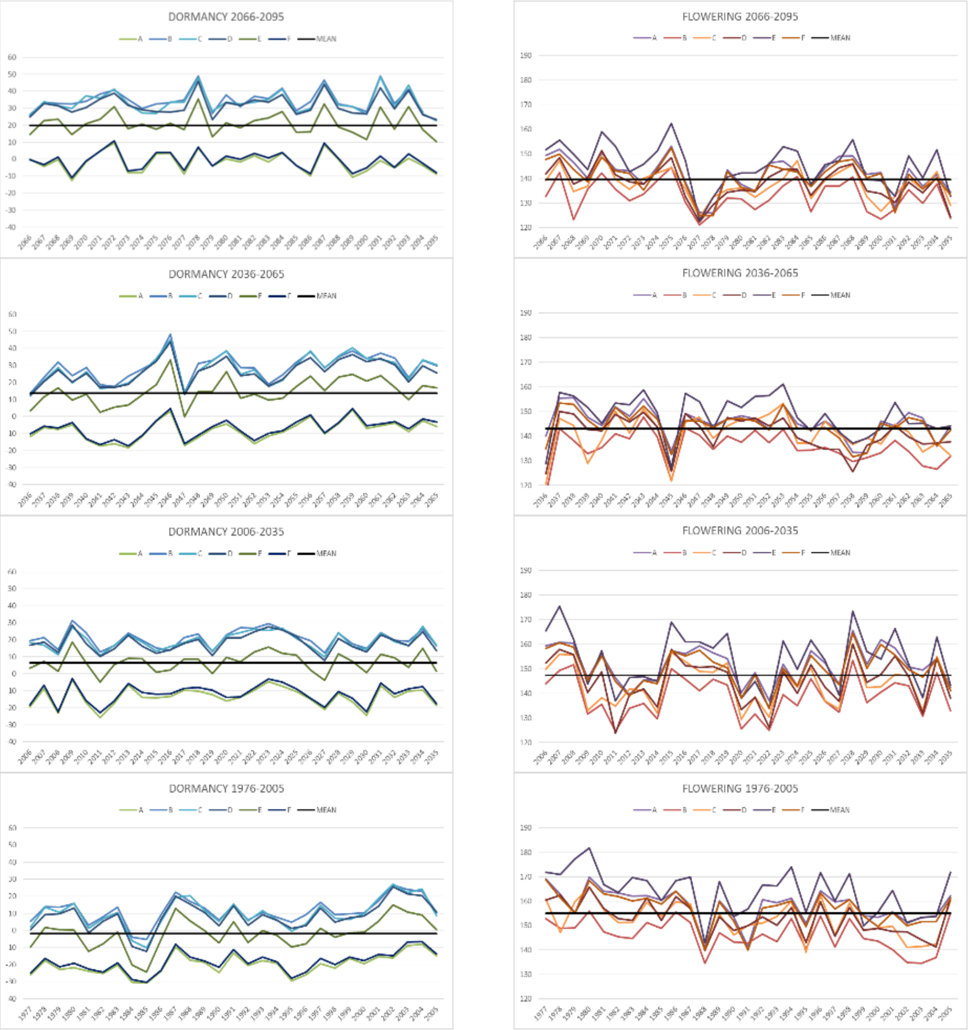




Graph 3.11a simulations results of the impact of climate change on Cannonau

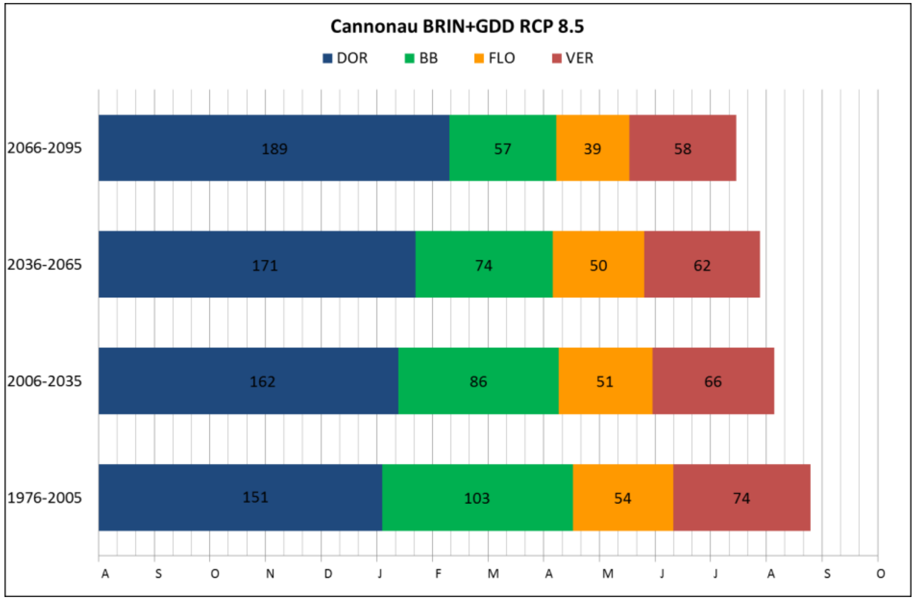


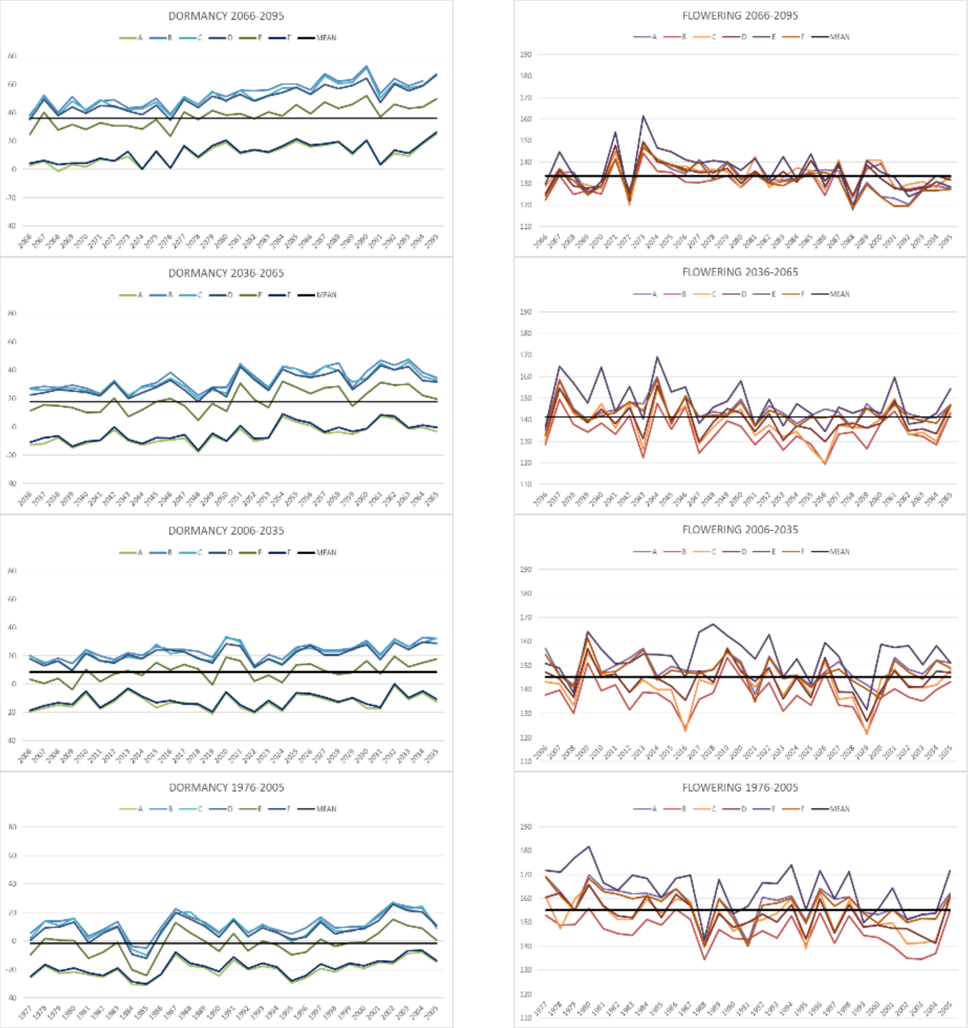
Graph 3.11b simulations results of Dormancy and Flowering phases through the different sites [A=Spresiano (TV); B=Villasor (CA); C=Jerzu (OG); D=Alghero (SS); E=Siniscola (OT); F=Barbarano Vicentino (VI)]



Graph 3.12a simulations results of the impact of climate change on Cannonau

Graph 3.12b simulations results of Dormancy and Flowering phases through the different sites [A=Spresiano (TV); B=Villasor (CA); C=Jerzu (OG); D=Alghero (SS); E=Siniscola (OT); F=Barbarano Vicentino (VI)]





Regarding the behaviour of Vitis Vinifera L. in the different sites, it will be possible to identify a sort of trend of responses according to the geographical positions of the station from North to Center and Italy Island.

In the Northern Italy sites [Tenuta Cannona (AL), Spresiano (TV), Barbarano Vicentino (VI)], the impact of climate change will be more intense than in the Center and Island sites [Latina (LT), Alghero (SS), Siniscola (OT), Oristano (OT), Jerzu (OG), Villasor (CA)], with the exclusion of one site in the Umbria region [S.Apollinare (PG)], which provided results more similar to the Piedmont and Veneto regions rather than to the Lazio and Sardinia regions.

The tables below summarize the phenological results according to the stages and the length of the phases in relation to the modifications that climate change may involve. The comparison between baseline scenario and the three future scenarios (recent future 2006-2035; future 2036-2065; far future 2066-2095), was analysed in all sites and for all varieties in the sites mentioned above. (Tables from 3.6 to 3.15).

Table 3.6a Phenological stages and length of the phenological phases (n° of days) for Tenuta Cannona (AL) - Piedmont region, for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Tenuta Cannona (AL)-Piedmont*											
variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	10	18	24	9	16	22	9	16	22	10	20	26
50%BB	-8	-13	-16	-9	-16	-18	-9	-15	-18	-7	-11	-13
50%FLO	-9	-14	-17	-9	-16	-19	-9	-16	-18	-8	-13	-16
50%VER	-16	-24	-27	-8	-14	-17	-10	-17	-19	-15	-22	-25
DOR-50%BB	-17	-32	-39	-18	-32	-40	-18	-32	-40	-17	-31	-39
50%BB-50%FLO	-1	-1	-2	0	0	-1	0	0	0	-1	-2	-2
50%FLO-50%VER	-7	-9	-10	1	2	2	-1	-1	-1	-6	-9	-9

Table 3.6b Phenological stages and length of the phenological phases (n° of days) for Tenuta Cannona (AL) – Piedmont region, for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Tenuta Cannona (AL)-Piedmont*											
variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	12	22	43	10	19	39	10	19	39	13	24	46
50%BB	-10	-17	-18	-14	-21	-20	-13	-20	-21	-10	-15	-12
50%FLO	-9	-16	-24	-12	-19	-24	-11	-18	-24	-9	-15	-19
50%VER	-15	-25	-35	-11	-17	-15	-12	-19	-22	-14	-23	-32
DOR-50%BB	-23	-38	-61	-24	-40	-59	-23	-39	-60	-23	-39	-58
50%BB-50%FLO	1	1	-5	2	2	-4	2	2	-3	1	0	-7
50%FLO-50%VER	-6	-9	-11	1	2	10	-1	-1	2	-5	-8	-13

Table 3.7a Phenological stages and length of the phenological phases (n° of days) for Spresiano (TV) – Veneto region , for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

Site	*Spresiano (TV) - Veneto*																	
variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon			Vermentino			Cannonau		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	9	15	22	8	14	20	8	14	20	9	17	24	6	11	17	7	12	18
50%BB	-6	-10	-14	-7	-11	-16	-7	-11	-16	-6	-9	-13	-8	-13	-18	-8	-12	-18
50%FLO	-6	-11	-15	-7	-12	-16	-7	-12	-17	-6	-10	-14	-8	-13	-18	-6	-13	-17
50%VER	-10	-17	-21	-5	-8	-13	-7	-12	-16	-9	-16	-20	-9	-12	-16	-12	-20	-24
DOR - 50%BB	-15	-25	-37	-14	-24	-36	-15	-25	-36	-15	-26	-37	-14	-24	-35	-15	-24	-36
50%BB - 50%FLO	0	-1	0	0	-1	0	0	-1	-1	0	-1	-1	0	0	0	2	0	1
50%FLO - 50%VER	-4	-5	-6	2	4	3	0	0	0	-4	-6	-6	-1	1	1	-5	-7	-8

Table 3.7b Phenological stages and length of the phenological phases (n° of days) for Spresiano (TV) – Veneto region, for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

Site	*Spresiano (TV) - Veneto*																	
variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon			Vermentino			Cannonau		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	11	20	40	9	18	37	9	18	37	12	22	43	6	13	28	7	14	31
50%BB	-8	-13	-18	-10	-16	-19	-9	-15	-20	-7	-12	-14	-10	-19	-30	-11	-18	-27
50%FLO	-8	-12	-21	-10	-14	-22	-9	-15	-22	-8	-12	-18	-10	-16	-28	-9	-14	-26
50%VER	-12	-18	-27	-8	-11	-8	-10	-14	-17	-11	-17	-27	-12	-16	-19	-14	-21	-38
DOR - 50%BB	-19	-33	-58	-19	-34	-56	-18	-33	-57	-20	-34	-57	-17	-31	-58	-18	-33	-58
50%BB - 50%FLO	0	1	-3	0	1	-3	0	1	-2	0	0	-4	0	3	2	2	5	1
50%FLO - 50%VER	-3	-5	-6	1	3	14	0	0	6	-3	-5	-9	-1	0	9	-4	-8	-12

Table 3.8a Phenological stages and length of the phenological phases (n° of days) for Barbarano Vicentino (VI) – Veneto region , for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Barbarano Vicentino (VI) - Veneto*		
variety	Cannonau		
phase	RF-B	F-B	FF-B
DOR	7	12	18
50%BB	-8	-12	-18
50%FLO	-7	-13	-17
50%VER	-12	-20	-24
DOR - 50%BB	-15	-24	-35
50%BB - 50%FLO	1	0	1
50%FLO - 50%VER	-5	-7	-7

Table 3.8b Phenological stages and length of the phenological phases (n° of days) for Barbarano Vicentino (VI) – Veneto region , for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Barbarano Vicentino (VI) - Veneto*		
variety	Cannonau		
phase	RF-B	F-B	FF-B
DOR	7	14	31
50%BB	-11	-18	-27
50%FLO	-9	-14	-26
50%VER	-13	-21	-37
DOR - 50%BB	-18	-32	-58
50%BB - 50%FLO	2	4	1
50%FLO - 50%VER	-4	-7	-11

Table 3.9a Phenological stages and length of the phenological phases (n° of days) for S. Apollinare (PG) – Umbria region , for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*S. Apollinare (PG) - Umbria*														
variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon			Vermentino		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	9	17	24	9	16	23	9	16	23	10	17	26	6	12	18
50%BB	-6	-10	-12	-7	-9	-13	-8	-10	-13	-6	-9	-10	-10	-15	-20
50%FLO	-7	-12	-16	-8	-12	-16	-8	-12	-16	-7	-11	-14	-9	-15	-20
50%VER	-13	-21	-24	-6	-9	-13	-8	-13	-17	-13	-20	-23	-11	-16	-20
DOR - 50%BB	-16	-27	-37	-16	-26	-36	-16	-26	-36	-15	-26	-36	-16	-28	-38
50%BB - 50%FLO	-1	-3	-3	-1	-3	-3	0	-2	-3	-1	-3	-4	1	0	0
50%FLO-50%VER	-6	-8	-9	1	3	3	-1	-1	-1	-6	-9	-9	-2	0	0

Table 3.9b Phenological stages and length of the phenological phases (n° of days) for S. Apollinare (PG) – Umbria region , for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*S. Apollinare (PG) - Umbria*														
variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon			Vermentino		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	12	22	44	11	20	41	11	20	41	13	23	46	7	14	31
50%BB	-8	-12	-14	-10	-14	-14	-9	-15	-16	-7	-11	-8	-13	-21	-31
50%FLO	-9	-14	-22	-10	-15	-21	-10	-15	-21	-8	-12	-17	-12	-18	-30
50%VER	-14	-22	-31	-9	-12	-9	-10	-16	-18	-13	-21	-29	-13	-19	-25
DOR - 50%BB	-20	-34	-58	-20	-35	-54	-20	-35	-57	-20	-34	-54	-20	-35	-62
50%BB-50%FLO	0	-2	-7	0	-1	-7	0	0	-5	-1	-2	-9	2	3	1
50%FLO-50%VER	-5	-8	-10	1	3	12	0	-1	3	-5	-8	-13	-1	-1	5

Table 3.10a Phenological stages and length of the phenological phases (n° of days) for Latina (LT) – Lazio region , for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Latina (LT) – Lazio*														
variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon			Vermentino		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	10	18	26	9	18	25	9	18	25	11	20	28	7	13	19
50%BB	-2	-6	-6	-3	-5	-4	-4	-6	-6	-2	-3	-2	-9	-14	-17
50%FLO	-5	-10	-12	-5	-9	-10	-5	-9	-10	-4	-8	-9	-8	-14	-18
50%VER	-9	-16	-18	-3	-6	-6	-6	-10	-11	-9	-15	-17	-9	-14	-17
DOR - 50%BB	-13	-25	-32	-12	-22	-29	-13	-24	-31	-13	-23	-30	-16	-27	-36
50%BB - 50%FLO	-3	-4	-6	-2	-4	-7	-1	-3	-4	-2	-5	-7	0	0	-1
50%FLO-50%VER	-4	-6	-6	2	3	4	-1	-1	-1	-5	-7	-8	-1	0	1

Table 3.10b Phenological stages and length of the phenological phases (n° of days) for Latina (LT) – Lazio region , for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Latina (LT) – Lazio*														
variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon			Vermentino		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	12	25	48	12	23	45	12	23	45	14	27	53	7	16	33
50%BB	-5	-5	0	-5	-6	1	-6	-8	-3	-3	-1	10	-14	-19	-23
50%FLO	-7	-10	-13	-7	-10	-11	-7	-10	-11	-6	-6	-4	-12	-16	-26
50%VER	-11	-16	-21	-6	-6	5	-8	-10	-7	-10	-14	-17	-12	-16	-22
DOR - 50%BB	-18	-30	-48	-17	-29	-43	-18	-31	-48	-17	-28	-44	-21	-35	-56
50%BB - 50%FLO	-2	-4	-13	-2	-4	-12	-1	-2	-8	-3	-6	-14	2	3	-3
50%FL 50%VER	-4	-6	-8	1	4	15	0	0	3	-4	-8	-12	-1	0	4

Table 3.11a Phenological stages and length of the phenological phases (n° of days) for Alghero (SS) – Sardinia region, for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Alghero (SS) – Sardinia*					
variety	Vermentino			Cannonau		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	9	16	21	10	18	23
50%BB	-4	-7	-7	1	-1	0
50%FLO	-7	-11	-13	-8	-12	-15
50%VER	-7	-12	-13	-12	-18	-22
DOR - 50%BB	-12	-23	-28	-9	-19	-23
50%BB - 50%FLO	-3	-4	-6	-9	-11	-15
50%FLO - 50%VER	-1	-1	0	-4	-6	-7

Table 3.11b Phenological stages and length of the phenological phases (n° of days) for Alghero (SS) – Sardinia region, for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Alghero (SS) – Sardinia*					
variety	Vermentino			Cannonau		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	11	20	38	13	22	42
50%BB	-7	-9	-5	-1	-2	6
50%FLO	-8	-12	-17	-9	-13	-19
50%VER	-9	-12	-14	-12	-20	-32
DOR - 50%BB	-17	-29	-43	-14	-24	-36
50%BB - 50%FLO	-2	-3	-12	-8	-11	-25
50%FLO - 50%VER	-1	0	3	-3	-6	-12

Table 3.12a Phenological stages and length of the phenological phases (n° of days) for Siniscola (OT) – Sardinia region, for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Siniscola (OT)) – Sardinia*		
variety	Cannonau		
phase	RF-B	F-B	FF-B
DOR	9	17	23
50%BB	-6	-11	-9
50%FLO	-10	-16	-18
50%VER	-16	-24	-28
DOR - 50%BB	-15	-28	-32
50%BB - 50%FLO	-4	-5	-9
50%FLO - 50%VER	-6	-8	-10

Table 3.12b Phenological stages and length of the phenological phases (n° of days) for Siniscola (OT) – Sardinia region, for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Siniscola (OT)) – Sardinia*		
variety	Cannonau		
phase	RF-B	F-B	FF-B
DOR	11	21	40
50%BB	-10	-13	-9
50%FLO	-11	-16	-28
50%VER	-16	-26	-42
DOR - 50%BB	-21	-34	-49
50%BB - 50%FLO	-1	-3	-18
50%FLO - 50%VER	-5	-10	-15

Table 3.13a Phenological stages and length of the phenological phases (n° of days) for Oristano (OR) – Sardinia region, for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Oristano (OR) – Sardinia*		
variety	Vermentino		
phase	RF-B	F-B	FF-B
DOR	8	16	21
50%BB	-4	-7	-6
50%FLO	-7	-11	-13
50%VER	-7	-10	-11
DOR - 50%BB	-12	-23	-28
50%BB - 50%FLO	-4	-4	-7
50%FLO - 50%VER	0	0	2

Table 3.13b Phenological stages and length of the phenological phases (n° of days) for Oristano (OR) – Sardinia region, for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Oristano (OR) – Sardinia*		
variety	Vermentino		
phase	RF-B	F-B	FF-B
DOR	10	20	38
50%BB	-7	-10	-5
50%FLO	-10	-14	-17
50%VER	-10	-12	-10
DOR - 50%BB	-18	-30	-43
50%BB - 50%FLO	-2	-4	-12
50%FLO - 50%VER	0	2	7

Table 3.14a Phenological stages and length of the phenological phases (n° of days) for Jerzu (OG) – Sardinia region, for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Jerzu (OG) – Sardinia*		
variety	Cannonau		
phase	RF-B	F-B	FF-B
DOR	9	18	23
50%BB	0	-2	0
50%FLO	-8	-12	-15
50%VER	-11	-17	-20
DOR - 50%BB	-9	-19	-23
50%BB - 50%FLO	-8	-10	-15
50%FLO - 50%VER	-3	-5	-6

Table 3.14b Phenological stages and length of the phenological phases (n° of days) for Jerzu (OG) – Sardinia region, for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

site	*Jerzu (OG) – Sardinia*		
variety	Cannonau		
phase	RF-B	F-B	FF-B
DOR	12	22	42
50%BB	-2	-3	6
50%FLO	-10	-14	-18
50%VER	-13	-20	-29
DOR - 50%BB	-14	-26	-36
50%BB - 50%FLO	-8	-11	-24
50%FLO - 50%VER	-3	-6	-11

Table 3.15a Phenological stages and length of the phenological phases (n° of days) for Villasor (CA) – Sardinia region, for RCP 4.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

Site *Villasor (CA) - Sardinia*

variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon			Vermentino			Cannonau		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	10	23	30	10	21	28	10	21	28	11	26	34	9	16	22	9	18	23
50%BB	1	6	9	3	6	10	2	4	7	3	12	16	-2	-5	-4	1	-1	2
50%FLO	-4	-3	-3	-1	-1	0	-2	-1	0	-2	2	5	-6	-10	-11	-7	-11	-13
50%VER	-7	-8	-8	2	6	9	-1	-1	2	-6	-5	-4	-5	-9	-10	-11	-16	-19
DOR - 50%BB	-10	-17	-21	-7	-15	-18	-9	-17	-20	-8	-14	-18	-11	-21	-25	-8	-19	-22
50%BB - 50%FLO	-5	-9	-12	-4	-7	-10	-3	-5	-7	-4	-9	-11	-4	-5	-8	-8	-10	-15
50%FLO - 50%VER	-3	-4	-4	3	7	9	0	1	2	-5	-7	-9	1	0	1	-3	-5	-6

Table 3.15b Phenological stages and length of the phenological phases (n° of days) for Villasor (CA) – Sardinia region, for RCP 8.5 scenarios (RF: Recent Future, F: Future, FF: Far Future) comparing to baseline (B)

Site *Villasor (CA) - Sardinia*

variety	Cabernet Franc			Chardonnay			Renan Riesling			Sauvignon			Vermentino			Cannonau		
phase	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B	RF-B	F-B	FF-B
DOR	15	31	61	14	28	55	14	28	55	17	35	72	11	20	39	12	22	43
50%BB	2	11	30	2	10	28	1	8	25	6	18	44	-4	-6	-1	-1	-1	9
50%FLO	-4	-1	10	-2	1	14	-2	2	15	0	7	31	-7	-11	-15	-9	-12	-15
50%VER	-6	-4	11	0	11	46	-2	4	29	-5	-1	25	-8	-9	-3	-11	-17	-27
DOR - 50%BB	-13	-20	-32	-12	-18	-27	-13	-20	-30	-11	-17	-27	-15	-27	-40	-13	-23	-34
50%BB - 50%FLO	-6	-12	-20	-4	-9	-14	-3	-7	-10	-6	-11	-13	-3	-5	-13	-8	-11	-24
50%FLO - 50%VER	-2	-4	1	2	10	32	0	2	15	-4	-7	-6	0	2	11	-2	-6	-12

The results clearly indicate the relationship between phenological stages and environmental temperature; therefore, the higher temperatures estimated by climate models cause an acceleration of the developmental rate of grapevine, revealing an elongation of the dormancy phase and a shortening of the vegetative phases. The reduction of the length of the growing season is well documented both in other continents by Webb, et al. (2011,2007) and in Europe (Duchêne et al. 2010; Garcia de Cortazar Atauri 2006; Duchêne & Schneider, 2005).

On the other hand, few studies have been conducted so far in Italy. However, the limited amount of such studies has been a limitation in comparing this study with other Italian researches. At regional scale, in fact, Fila et. al (2014) and Tomasi et al.(2011) analysed the impact of climate change on grapevine on few varieties per time.

Fila et al. (2014) have observed a progressive advance in phenological timings for Chardonnay variety, in Veneto region. Particularly, considering the century between 1990 - 2090 for SRES-A2 emission scenario, were observed a prediction at 2090 of the budburst time from 13.9 to 44.4 days earlier than 1990; an advance between 24 and 36.5 days for flowering and among 29 and 43 days for veraison.

Again in Veneto region, Tomasi et al. (2001) compared eighteen different grape wine varieties in the 1964–2009 period. In such study was highlighted the capability of the vineyard at modify the growth cycle according to the climate variations. In these forty five years, in accordance with the climate warming, was observe an advance of flowering and veraison phases and an elongation of the dormancy phase, specific for each variety.

Conclusions

This study aimed to assess different phenological models so as to represent the growth life cycle of grape and, after that, simulate the impact of climatic change on Vitis Vinifera L. according to different climate scenarios.

As a result, the BRIN model has revealed a high variety of response of different grape cultivars, and, in relation to the comparison, only three of six models performed well in our study. Hence, these models were linked with the dormancy model in order to obtain the complete models that may represent the whole grapevine growth cycle. Also in accordance with other researchers, the BRIN model and the beta model WANG040 were revealed good performance to modelling the grapevine life growth cycle.

Thanks to these representations, in the second part of this study, it was possible to simulate the impact of climate change on grapevine in Italy. The varieties that present an overall RMSE higher than 30 days have been excluded in order to have plausible results.

The analyses revealed a gradual shortening of the growth cycle to the detriment of the vegetative phases, with a higher intensity in RCP 8.5 than RCP 4.5; such trend is visible more intensively in the northern sites than in centre Italy and in Sardinia island.

This study has allowed a comparison between different models so as to underline the interconnection between phenology and temperature, and it has also allowed to observe how temperature may influence the entire cycle growth of the plant. In future scenarios, the increase of temperature will be a reason (factor, cause) for evident imbalances in terms of plant development and, as a consequence, fruit quality.

Chapter 4: Modelling phenology and yield of Sardinian grapevine

Introduction

The fifth assessment report (AR5) of the IPCC (Intergovernmental Panel on Climate Change) summarizes the knowledge acquired to date on climate change and its consequences in the world. In this report the influence of human activities on global climate is unequivocally confirmed. Global climate is characterized by natural changes that interest long time periods (from few years to millions of years) but, according to AR5, since 250 years the climate was altered by greenhouse gas emissions of anthropic derivation; these gas modified progressively the atmospheric composition and caused considerable change with uncertain effects. (IPPC, 2014)

Over the last years, particular consideration was given to the study of climate change impact on agriculture and adaptation strategies in different areas (Anwar, et al., 2013).

As regard for the grapevine cultivation, especially the seasonal anomalies, in terms of drought in spring-summer time and mild winter, have helped to increase the debate on the impact of climate change in wine-growing areas (Moriondo, et al., 2013; Anderson, et al., 2008; Jones, 2007). A very interesting overview was done by H. Fraga et al. (2012), underlining the close dependence of viticulture on climate, and the importance to consider different measures in terms of adaptation and mitigation strategies.

In addition, it is important to consider the interactions between soil, genotypes and management. In order to combine the overall interaction between one crop and its environment the only option is to resort to use a mechanistic model, whereby it is possible to integrate the complexity of potential interactions (Seguin & Garcia de Cortazar, 2005); therefore, many crop-models have been developed to simulate different conditions in the agronomic field. Several studies conducted on the simulation of herbaceous crops, mainly cereals (Confalonieri, et al., 2009; Jones, et al., 2003; van Diepen, et al., 1989), have been instrumental to comprehend plant reaction to possible climate scenarios (Palosuo, et al., 2011; Mereu, 2010). However, the approach relating to tree crops is less developed. This is attributable to both their physiological complexity and because of the difficulty to produce and obtain data that can be implemented in different models. Therefore the scientific community is moving towards more comprehensive models, defined as generic crop simulators, which enable using a common set of parameters to simulate different crop (Bellocchi & Maestrini, 2002).

As reviewed by Moriondo et al. (2015) few crop model were developed for grapevines; such models allow the simulation of the whole of crop growth cycle in relationship with the environment.

The first grape model approach, developed by Gutierrez et al. (1985), presents a mathematical structure model to mimic grape growth and its development. Afterward Wermerlinger et al. (1991) and Bindi et al. (1997) have been proposed their models for the simulation of grapevine growth, but all these models did not considered the root-soil system and the different stress of the plant, in terms of nutrient and water dynamics. Other authors implement their models with water balance (Lebon, et al., 2003), nitrogen balance (Nendel & Kersebaum, 2004) or both (Ben-Asher, et al., 2006), others focused on particular topics, such as daily CO2 balance (Poni, et al., 2006), relationship between grape and grass in intercropping systems (Ripoche, et al., 2011) (Celette, et al., 2010) and partition of biomass to different organs (Pallas, et al., 2011). Among the available moedels, Vinelogic (Godwin, et al., 2002), CropSyst (Stockle, et al., 2003) and STICS (Brisson, et al., 2008) are able to simulate, more or less, whole exchange processes between crop and environment.

However, as these models describe the processes on a high level of detail and a relatively large number of input variables was required, Cola et al. (2014) developed a dynamic crop model with a minimal requirement of input data.

In this framework, the crop model STICS, was selected in this study to simulate the impact of climate change on vineyard in Sardina Island, in order to provide some information about changes in phenology and yield.

Materials and methods

The analysis is composed by different steps:

- Implementation in the Stics model for a new cultivar, Cannonau variety, which is one of the most diffused grapevine variety in Sardinia
- Analysis of the yield responses under climate change conditions of Cannoanu and Cabernet Franc (already implemented in Stics model).

Crop model: STICS

The STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) soil–crop model has been developed since 1996 (Brisson et al., 1998, 2002, 2003, 2008) at the National Institute of Agronomical Research (INRA) in France. It is a free-software available on the web at http://www6.paca.inra.fr/.

The STICS system and its components have been described in details in Brisson, et al.(2008). Stics is a tool the allows to simulate the main crop processes, as growth and development, and water and nitrogen balances. STICS is a daily time-step model organised into four main modules: Ecophysiology of above-ground plant parts (phenology, shoot growth, yield formation), Soil module (root growth, water balance, nitrogen balance, soil transfer), Crop management module, where the interactions between the different techniques and the soil-crop system are analysed, and the Microclimate module that simulates the combination between climate and water balance on temperature and the air humidity inside the canopy. STICS is also easily adaptable to various types of plants; in fact, in its latest version it is possible to find up to twenty different species of plants.

Garcia de Cortazar-Atauri (2006) in his PhD thesis developed the grapevine subdivision of the model, where the STICS-software-code was adapted to a perennial plant. Thanks to this study, STICS was implemented with eight varieties of grapevine (Cabernet Franc, Chardonnay, Chenin, Grenache, Merlot, Pinot Noir, Syrah, Ugni Blanc). In such a way it was possible to analyse the role of climate and weather factors throughout the grape growth in terms of phenological stages (Garcia de Crotazar-Atauri, et al., 2009a) as well as the maturation of the grape berries in relation to growth, development and evolution of water content (Garcia de Crotazar-Atauri, et al., 2009b).

In this work, the latest version of the model (JavaStics 1.x / Stics v8.x) has been used.

The first objective was the implementation of an additional variety of grape, the Cannonau, which is one of the most important varieties of grapevine cultivated in Sardinia.

The Cannonau variety was implemented starting from the Grenache variety already implemented and tested in Stics model.

The varietal coefficient for phenology were identified with a cross-validation method (leave one out), fitting the observed data (Tab.4.2) using PMP (Phenological Modelling Platform) Software v.5.5 (Chiune, et al., 2013), according to the Growing Degree Day model, with a base temperature of 10°C, or rather, the same phenological model implemented in STICS.

The STICS-cultivar parameters obtained consist in the following values (Tab. 4.1), expressed in degree-day, according to STICS' User Guide:

Table 4.1: STICS' parameter used

Variety	*unit*	*Cannonau*
Stdordebour	Degree/day	12544.4
Q10	-	2.17
Idebdorm	Julian day	-153
Stamflax	Degree/day	1353.2
Stlevdrp	Degree/day	461.4
Stflodrp	Degree/day	154
Dureefruit	Degree/day	1323.6

Where:

Stdordebour: cumulative thermal time between the dormancy break and the bud break
Q10: Q10 used for the dormancy break calculation
Idebdorm: day of the dormancy entrance
Stamflax: cumulative thermal time between the stages AMF (maximum acceleration of leaf growth, end of juvenile phase) and LAX (maximum leaf area index, end of leaf growth)
Stlevdrp: cumulative thermal time between the stages LEV (emergence) and DRP (starting date of filling of harvested organs)
Stflodrp: cumulative thermal time between the stages FLO (flowering) and DRP (starting date of filling of harvested organs)
Dureefruit: total growth period of a fruit at the setting stage to the physiological maturity.

Regarding the yield, the parameters of Grenache cultivar were used and the model was tested by comparing the yield data with the information available in the production disciplinary, which allows a maximum yield of 9-11 t/ha for the Cannonau variety. Moreover, the Cabernet Franc variety, already implemented in the model, was also considered.

Regarding the Cannonau variety, some bibliographical information regarding the weight of berry grape, indicated as 1.96 gr for the Cannonau variety, was found in Nieddu et al. (2011); in addition, the Jerzu and Alghero studies report plant density and number of inflorescences.

In addition, in the model were considered the management decisions in accordance with the original studies (Tab.3.1. References).

Information for the adopted management were derived by CONVISAR (2012). The Guyot training system, with a winter pruning, and a regulated deficit irrigation with a threshold of 0.6 (adimensional variable between 0 and 1) is the ordinary management in Sardinian grapevine.

Concerning the Cabernet Franc varieties already implemented in STICS the information available in the production disciplinary of "Alghero DOC" was considered for production values. In this document, in fact, were reported the maximum yield authorized for «Alghero» Cabernet (13.0 t/ha).

In order to verify the ability of the model to simulate mean yield values, two different sites were considered. In those, a ten-years meteorological data series was simulate.

After that, the impact analysis was simulated in climate change condition scenarios, in order to evaluate changing in yield in the particular situation of no soil tillage techniques.

Study area

The study sites are located in the middle of the Mediterranean Sea, in Sardinia (Italy). The region of Sardinia is the second island of the Mediterranean Basin, extending for 24.098 kmq, subdivided in 18% of flat land, 68% of hilly land and only 14% of mountain areas. The Sardinian climate is basically subdivided into two main seasons: one warm and dry and, at the opposite, the other cold and humid.

The yearly temperatures, on average, vary between 17-18°C, in warmer coastal areas, and 10-12°C, in the mountain areas around 1000m of altitude. The precipitations increase according to altitude and vary between 433 mm in south-west costal area and 1412 mm in the northern part of the island at 1000 m.a.s.l. Nevertheless, the summer aridity phenomena affect the island from three to five months per year (Camarda, et al., 2015). For these characteristics, the Sardinian island climate is classified as Mediterranean, and, according to Canu et al. (2014), with 43 isobioclimates.

For this study, the data were collected from the available bibliography for the Cannonau wine grapes, as described in table 4.2.

Table 4.2: study sites information

CANNONAU

SITE	ALGHERO (SS)	JERZU (OG)	SINISCOLA (NU)	VILLASOR (CA)
YEAR	2005;2006	2004-2006	2000-2003	1998;1999
Meteo stations	Alghero airport	Jerzu	Siniscola	Cagliari airport
Site Coordinates	23 m.a.m.s.l. 40°38′22.74″ N 8°17′33.12″E	46 m.a.m.s.l. 39° 47' 28.983" N 9° 36' 20.189" E	14 m.a.m.s.l. 40° 35' 41.321" N 9° 43' 37.156" E	28 m.a.m.s.l.. 39°20′38.28″ N 8°58′14.52″E
Soil data information	available in associated study	available in the study	wise database	wise database
Management information	available in the study	available in the study	available in associated study	available in associated study
REFERENCES	Gometz, 2005-2006	Tomasi, et al., 2012	Cossu, et al., 2004	Phenagri project

Moreover, were consideredtwo hypotetical sitesfor ten years period in order to verify the ability of the model to simulate mean yield values As regards the Cannonau variety the model simulate the yields in the period between 1997 and 2007 in Oristano site, and for the Cabernet Franc variety the yields was verified in Alghero site between 1999 and 2008. Following the characteristics of the sites

For Oristano site, soil data was collected from ISRIC-WISE soil profile database, version 3.1(N.H.Batjes, 2012), while the meteorological data were obtained from Banca Dati Agrometeorologica Nazionale (BDAN) for Zeddiani – Santa Lucia station (14 m.a.m.s.l. 39°58' N 8°37'E).

Concerning Alghero site, the information considered were derived by Gometz et al. (2005 - 2006) (Tab.4.2)

Climate data

Climate data used in this study derive from the Regional Climate Model (RCM) COSMO-CLM at 14 km of resolution (Bucchignani et al.2014), for the historical (1976-2005) and future periods (2006-2035; 2036-2065; 2066-2095), considering two representative concentrations pathways (RCP) scenarios [RCP 4.5 (500 ppm CO2eq) and RCP 8.5 (1370 ppm CO2eq)].

Statistical approach

The model was tested using different indicators to evaluate the ability of the model to depict the observed data, and the capability to represent the atmosphere-soil-crop system.
For that reason, the selected indicators were:

- Minimum, maximum, mean value and standard deviation for observed and simulated data, to have information about the representative samples.
- Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) to give an estimation of the deviation between simulated and observed data;
- Pearson's coefficient (r) and the coefficient of determination (R2), to provide information about the correlation between estimated and measured values.
- the probability of observed and simulated data have equal means, that is Student t-test (P(t))

Table 4.3: Metrics' description

Statistic	*Equation*	*Value range and purpose*
RMSE	$RMSE = \sqrt{\frac{\sum_{i=1}^{n} E_i - M_i{}^{2}}{n}}$	represents the typical size of l error, with values equalling or zero indicating perfect or near perfect estimates
MAE	$MAE = \sum_{i=1}^{n} \frac{\lvert E_i - M_i \rvert}{n}$	values near or equal to zero indicate a better match along the 1:1 line comparison of estimated and observed values
r	$r = \frac{\sum_{i=1}^{n}(E_i - \overline{E}) \times (M_i - \overline{M})}{\left[\sum_{i=1}^{n}(E_i - \overline{E})^2 \times \sum_{i=1}^{n}(M_i - \overline{M})\right.}$	-1 (anti-correlation) to 1 (perfect correlation): the closer the values are to 1, the better performing the model
R^2	$R^2 = \frac{\sum_{i=1}^{n}(E-\overline{M})^2}{\sum_{i=1}^{n}(M-\overline{M})^2}$	R-squared values range from 0 to 1. An R-squared of 1 means that all movements of a security are completely explained by movements in the index. A high R-squared (between 0.85 and 1) indicates the fund's performance patterns have been in line with the index.
P(t)	$P(t) = \frac{\lvert\bar{D}\rvert}{s.e.(D)}$	0 (absence of agreement) to 1 (perfect agreement): the closer the values are to 1, the better performing the model

E: estimated value
M: measured value
n: number of observation
$\overline{E}$: mean of estimated values
$\overline{M}$: mean of measured values
n: number of observation
D: difference between estimated and measured values (residues)
$\overline{D}$: mean of D
s.e.(D): standard error of model residual

Parametrisation and verification of STICS model for the Cannonau variety

Phenological results

The model performances were determined using the statistical indexes described above for the flowering and harvest phases.

In the Cannonau variety, minimum and maximum values registered for flowering and harvest show good performance of the model to represent the observed data. The mean values, in fact, show a difference of only one day for the flowering phase and of five days for harvest. The standard deviation reveals good performance for the model to represent the flowering phase, but less variability in the simulation of harvest values (Tab.4.4).

Table 4.4: statistics of phenological phases for Cannonau variety, expresses in days

Stage		*Min*	*Max*	*Mean*	*SD*
FLO	Obs	137	164	147	8.55
	Sim	130	158	146	6.78
HAR	Obs	253	286	263	11.20
	Sim	257	278	268	5.58

The RMSE value reveals a good correspondence between observed and simulated data for the flowering phase with a difference lower than one week (5.72); rather good is the result for harvest date with an RMSE lower than 10 days (9.57). Similarly, MAE gives back the same trend as RMSE, with a flowering result better than harvest. Both reveal a good performance of the model to represent the deviation between simulated and observed data. The coefficient of determination R2 indicates that the model explains 56% of flowering variation and 52% of harvest variation. Moderately good are the results of Pearson r test, which reveals a correlation between observed and simulated values; the P(t) test indicates a good probability that observed and simulated data have equal means for flowering, but in harvest phase that relation diminishes, as already shown in tab.3.4 (Tab.4.5).

Table 4.5: statistics of phenological phases for Cannonau variety, expresses in Julian day

statistics	*FLO*	*HAR*
RMSE	5.72	9.57
MAE	4.60	8.76
R^2	0.56	0.52
r	0.75	0.72
P(t)	0.58	0.18
N°obs	12	10

These results appear satisfactory also in light of the fact that Garcia de Cortazar Atauri (2006) and Fraga et al. (2015) have observed an RMSE of 1.95 in France, the first, and the second 7.85 in Portugal, for flowering timing; and 9.28 and 2.38 for harvest date, respectively.

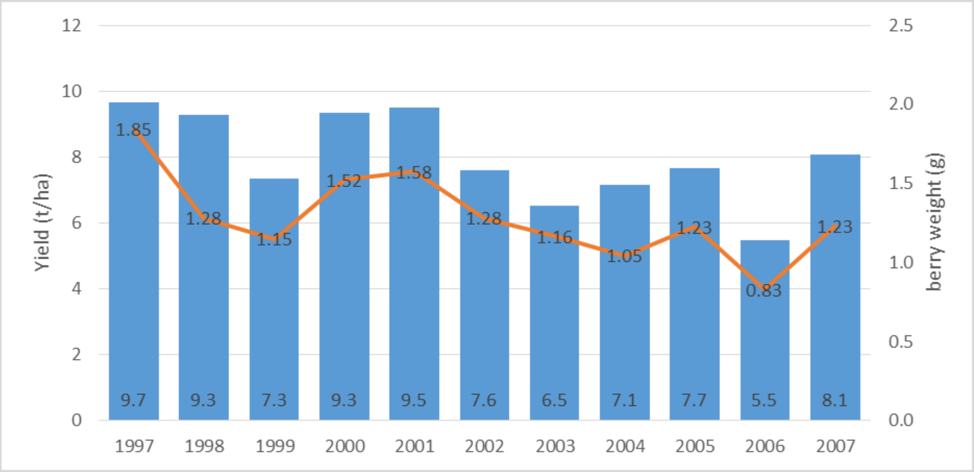
Fraga et al. (2015) also reported the coefficient of determination (R2) for flowering (0.35) and harvest (0.65) data.

Yield results

One field site was considered to verify the yield value for Cannonau variety. The results show (Graph. 3.1) a good trend of the model to represent the interannual successions of yields and berry weight. The average of the yields value is 7.96 t/ha and 1.29 grams is the mean of grapes weight. Similar mean values were obtained by Lovicu et al. (2011) for Cannonau production (8.5 t/ha) between 2007 and 2009 in Parteolla, a wine-growing region of southern Sardinia; in the same area Convisar (2012) identified a berry weight of 1.8 grams, but in Gallura and Sulcis regions this value vary between 2.3 and 1.4 grams respectively.

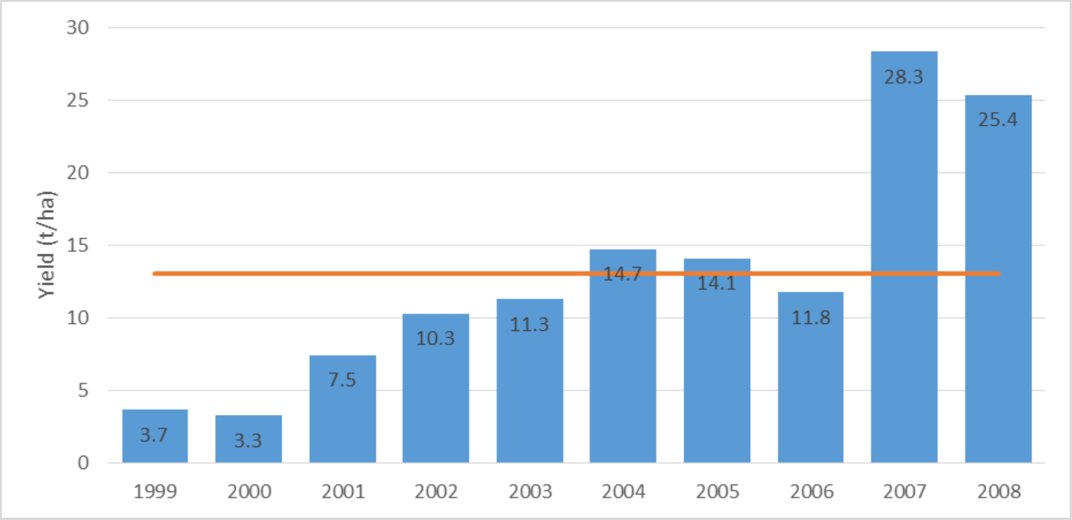
According to the disciplinary of production and the authors cited above, the main results obtained by verification analysis will be considered satisfactory for the purpose.

Graph 4.1: trend of Cannonau productions [Yield (t/ha) and berry weight (g)] in Oristano site between 1997 and 2007



Concerning the Cabernet Franc variety, the model performance show that the yield mean value correspond to the limit allow by the disciplinary of production (13.0 t/ha) (Graph 4.2).

Graph 4.2: trend of Cabernet Franc productions [Yield (t/ha)] in Alghero site between 1999 and 2008



Impact of climate change on Cannonau and Cabernet Franc varieties

In this section, the impact of climate change in terms of biomass and productivity variations has been analysed.

The results show the impact on each single variety as mean values of the thirty-year period for the variables mentioned above.

Impact on Yield

The impact of climate change on different grapevine varieties appears uniform in the mean values. For all varieties, in fact the variations in terms of production during the different periods do not change substantially. The percentage of variation is about 10%, in absolute value, for every thirty-year period. Nevertheless, the relative variations of the single sites appear much more influenced by the climate actions.

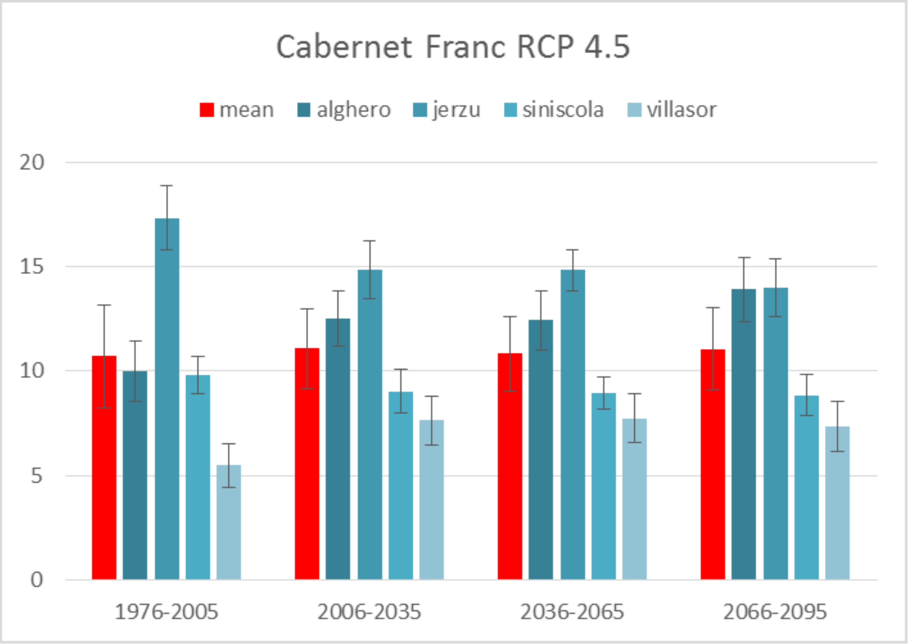
The station that presents the highest values of production is Jerzu for baseline period for each variety and scenarios analysed (17.3 t/ha for Cabernet Franc, 14.6 t/ha for Cannonau). While the lowest results were obtained in Villasor station for baseline period for Cabernet Franc (5.5 t/ha), while in the long-term period (2066 - 2095) for the Cannonau variety (4.2 t/ha).

The responses trend at climate modifications is divisible into two main group for RCP 4.5 scenario, the first group with Alghero and Villasor stations, and the second with Siniscola and Jerzu stations. The first group highlight a tendency to increase the rate of production during the future periods. On the other hand, in the second group the yield decreases with the periods.

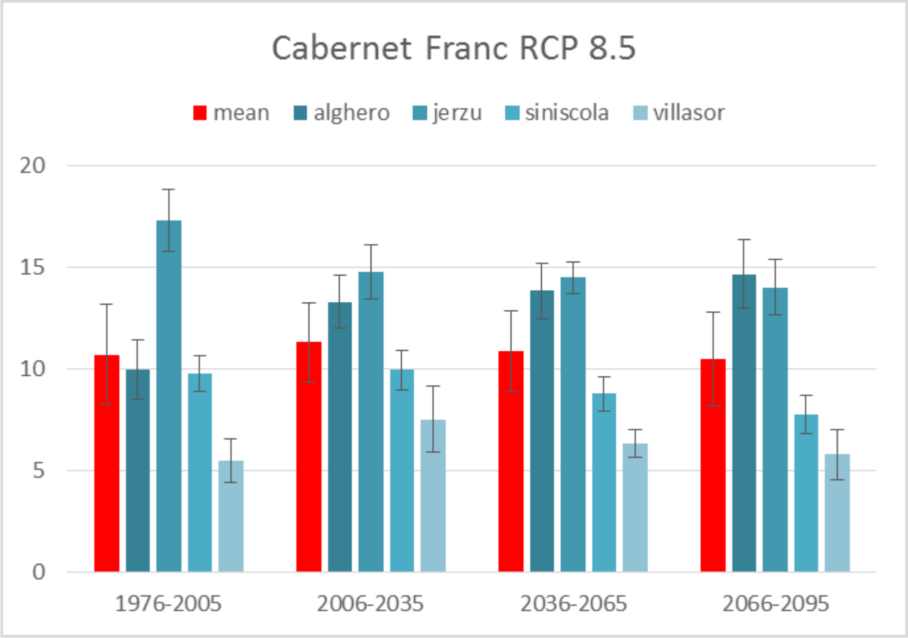
Much more complex appear the results for RCP 8.5, where the Jerzu and Siniscola stations mimic the same trend of the RCP 4.5 scenarios for all varieties. The Alghero station provides an increasing trend for the Cabernet Franc and Cannonau varieties. Similarly, Villasor site has a varying development through the different period with a peak in the short time period (2006 - 2035) for all varieties considered (7.5 t/ha for Cabernet Franc, 5.6 t/ha for Cannonau) (Graphs 4.3-4.4).

Graphs 4.3a, 4.3b : impact of climate change on Cabernet Franc for RCP 4.5 and RCP 8.5 scenarios

4.3a

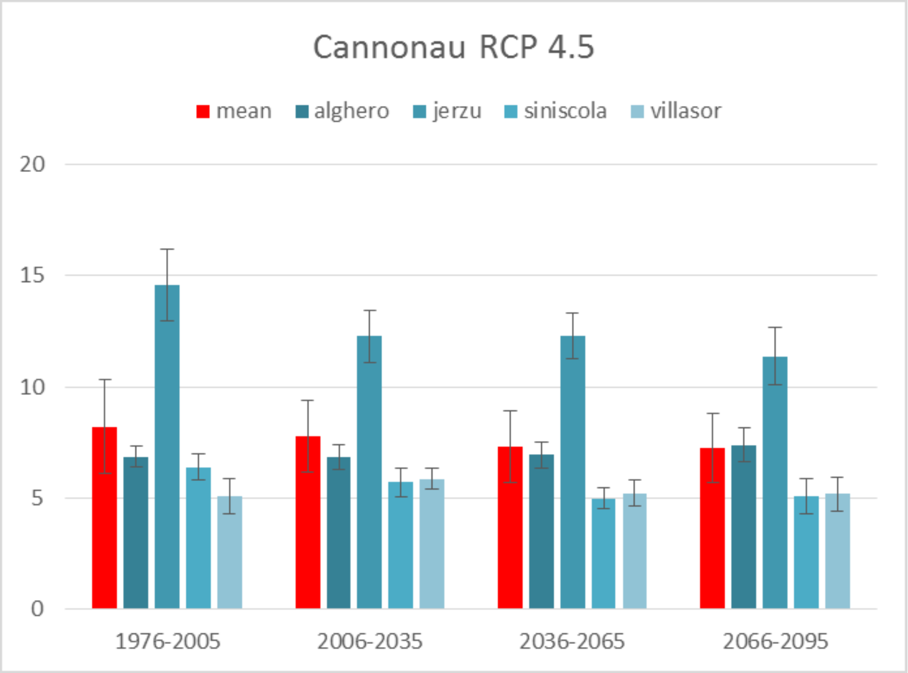


4.3b

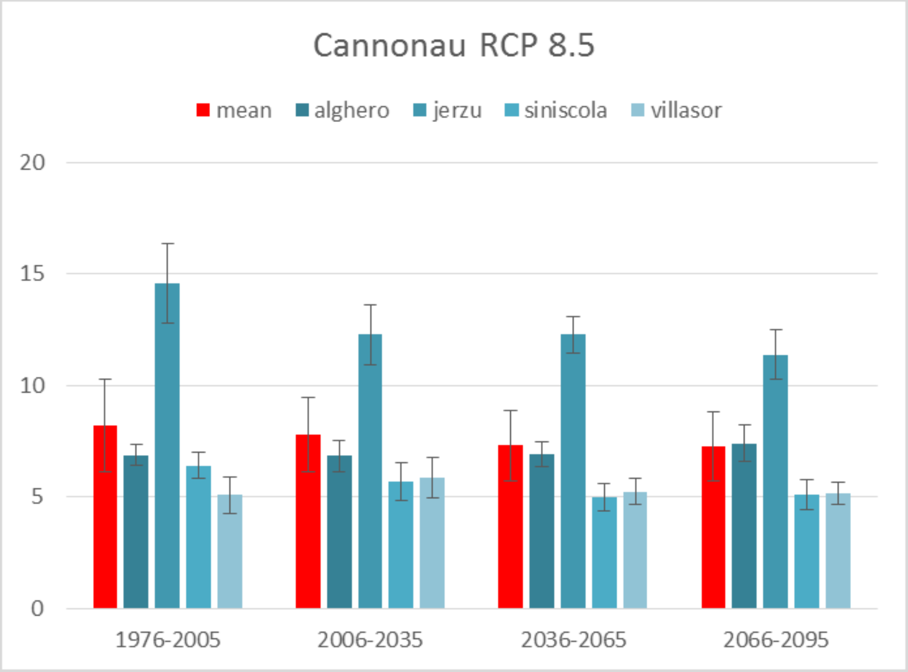


Graphs 4.4a, 4.4.b : impact of climate change on Cannonau for RCP 4.5 and RCP 8.5 scenarios

4.4a



4.4b



The results showed a constant tendency of yield through the different conditions analysed. That information is in line with the results identified obtained by Parra et al. (2010) in the Navarra region for Tempranillo grapevine, Lobel at al. (2006) in California and Garcia de Cortázar Atauri (2006) for the Languedoc and Cotes du Rhone regions. Such authors, in fact, did not identified significant variations across the different periods with different CO2 concentration scenarios. Conversely, Bindi et al. (1996) in Italy and Santos (2011) in Portugal predicted an increase in grape production.

Conclusions

In this study, the STICS crop model was used in order to analyse different climate change conditions in Sardinia. For this reason a new grape variety, the Cannonau, was implemented in the model, starting from bibliographic information. The crop model allows simulating the interactions between soil, climate, plant and management. Thus, it was possible to simulate the effect of climate change on the Cannonau variety and the other cultivar already implemented in the model: Cabernet Franc.

The parameterization and verification processes have allowed implementing the Cannonau variety in the STICS model. This process has enabled to identify four different sites in which the impact and mitigation strategy simulations have ran (Alghero, Jerzu, Siniscola and Villasor).

The impact results have shown almost a constant trend for the yield for the varieties, an increase in biomass reserves and a decrease of humified carbon in the soil.

Conversely, applying the fescue-grass intercrop mitigation strategy, the yield registered an increase on average values, this, maybe, to the detriment of the accumulation of reserves in biomass organs. However, such decrease is considered in percentage; in relative terms, the amount of initial reserve in intercrop situation reveals much higher values than the grapevine biomass without the associated plant.

Concerning the humified carbon in the soil, the results of the simulations for all varieties are almost the same for both impact and mitigation strategy conditions.

Conclusions and perspective

In this research, different tools and approaches were considered in order to analyse the impact of climate change on Vitis vinifera L., at different scales, in the Mediterranean area.

At European scale, three different bioclimatic indices were combined with pedological information in order to assess the suitability for grapevine under present climate conditions and with future climate change scenarios. The results show a northward shift of the suitable areas for grapevine cultivation.

At national scale (Italy), different phenological models were evaluated so as to represent the growth life cycle of grape. BRIN model and WANG040 revealed good performances in reproducing the observed phenological phases and were selected to simulate the impact of climate changes on grapevine phenology. The analyses revealed a gradual shortening of the growth cycle and a consequent increase of dormancy phase length, with a higher intensity in RCP 8.5 than RCP 4.5.

At regional scale (Sardinia), was used the STICS crop-model in order to evaluate the impact of climate change on the Cannonau e Cabernet Franc yield rates. In that section the results have shown almost a constant trend for the yield,

The different tools and methods applied in this study allowed to investigate various aspects of climate change impacts on grapevine.

Indeed, the identification of the future viticultural zones and the classification of suitable areas according to specific grapevine varieties permits to give information of the most suitable varieties for each area, providing useful information for both farmers and policymaker.

In addition, the analysis of the effects of climate change on grapevine growing cycle and yield allows to guide crop management and find reliable adaptation and mitigation strategies strategies to cope with climate change.

Moreover, the use of high-resolution, bias corrected, climate data (14 km), allowed to achieve detailed information useful to support planning and decision making process.

Additionally, the climate projections under RCP 4.5 and RCP 8.5 scenarios considered are in compliance with the new AR5, for that reason, this research is in the vanguard compared to the other studies.

In future studies will be possible to investigate many other aspects of grapevine sphere. At wide scale will be possible to subdivide the HI index into two low more class (1500- 1200; 1200 -

900) in order to identify much more precisely the viticultural zones. According to the suitability map obtain, the maps for each class of HI requirement may be realize, in order to understand better the evolution of single class of grapevine.

With a higher dataset available, will be possible increase the number of varieties studied in order to obtain cluster of plausible development of growth cycle according to the different thermal requirement.

In addition, with the aid of crop-model, several adaptation and mitigation strategies, according to crop management or genetics variables, might be simulate.

All of these ideas may additionally refine using an ensemble of climate models in order to diminishing the projection uncertainty.

References

AA.VV. (2008). La vite e il vino. Bologna: ART Servizi Editoriali S.p.A.

AA.VV. (2010). La zonazione della DOC Colli Berici - Manuale d'uso del territorio. Veneto Agricoltura Settore Economia, Mercati e Competitività.

Al Fajarat, M., Mohammad, A., Diabat, A., & Al Ibraheem, H. (2015). Developing a land suitability index for agricultural uses in dry lands from geologic poit of view usign GIS - a case study from Jordan. Indonesian Journal on Geoscience, 2(2), 63-75. doi: DOI:10.17014/ijog.2.2.63-76

Allen, R. G. (2005). A Landsat-based energy balance and evapotranspiration model in Western US water rights regulation and planning. Irrigation and Drainage Systems, 251-268.

Amerine, M. A. (1944). Composition and quality of musts and wines of California grapes. University of California.

Anderson, K., Findlay, C., Fuentes, S., & Tyerman, S. (2008). Viticulture, wine and climate change . Garnaut Climate Change Review, 01-16.

Anwar, M., Li Liu, D., Macadam, I., & Kelly, G. (2013). Adapting agriculture to climate change: a review. . Theoretical and applied climatology,(113(1-2)), 225-245.

Ayalew, G., & Selassie, Y. (2015). Land suitability evaluation for cereal and pulse crops using geographical information system in east Amhara region, Ethiopia. Research journal of agriculture and environmental management, 4(3), 141-148.

Batjes, N. H. (2012). ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid (ver. 1.2). ISRIC.

Bellocchi, G., & Maestrini, C. (2002). Principi di modellizzazione della crescita e dello sviluppo di specie arboree. Rivista di Agronomia, 1-16.

Ben-Asher, J., Van Dam, J., Feddes, R., & Jhorar, R. (2006). Irrigation of grapevines with saliner water: II. Mathematical simulation of vine growth and yield. Agricultural water management, 83(1), 22-29.

Bernetti, I., Meneghini, S., Marinelli, N., Sacchelli, S., & Sottini, V. (2012). Assessment of climate change impact on viticulture: Economic evaluations and adaptation strategies analysis for the Tuscan wine sector. Wine EconomicsandPolicy, 73-86.

Bernstein, Z. (1984). L'amelioration de la regularite de debourrement dans les regions a hiver doux [dormance, periode de taille, acide cyanamide, levee de la dormance chez la vigne; Israel]. Bulletin de l'OIV.

Bidabe, B. (1965). L'action des températures surl'évolution des bourgeons de l'entrée en dormance à la floraison. Congrès Pomologique, (p. 51-56).

Bidabe, B. (1965a). Contrôle de l'époque de floraison du pommier par une nouvelle conception de l'action des températures. CR Acad Agric Fr, 934 - 945.

Bindi M., M. F. (1997b). A simple model for simulation of growth and development in grapevine (Vitis vinifera L.). I. Model description. . Vitis, 67 - 71.

Bindi, M., & Olesen, J. (2011). The responses of agriculture in Europe to climate change. Regional Environmental Change(11.1), 151-158.

Bindi, M., Fibbi, L., Gozzini, B., Orlandini, S., & Miglietta, F. (1996). Modelling the impact of future climate scenarios on yield and yield variability of grapevine. Climate Research, 7, 213-224.

Bindi, M., Miglietta, F., Gozzini, B., Orlandini, S., & Seghi, L. (1997b). A simple model for simulation of growth and development in grapevine (Vitis vinifera L.). II. Model validation. vitis-geilweilerhof-(36), 73-76.

Bois, B. (2007). Ce que nous apprennent le climat récent et les observations phénologiques sur les effets du changement climatique en Gironde viticole. Actes de la 8ème Journée Technique du CIVB, 72 - 80.

Bonfante, A., Basile, A., Langella, G., Manna, P., & Terribile, F. (2011). A physically oriented approach to analysis and mapping of terroirs. Geoderma, 167, 103-117.

Brisson, N., Launay, M., Mary, B., & Beaudoin, N. (2008). Conceptual basis, formalizations and parametrization of the STICS crop Model. Versailles: Quae.

Brisson, N., Ruget, F., Gate, P., Lorgeou, J., Nicoullaud, B., Tayot, X., . . . Justes, E. (2002). STICS: a generic model for simulating crops and their water and nitrogen balances. II. Model validation for wheat and maize. Agronomie(22), 69-92.

Brunetti, M. M. (2002). Droughts and extreme events in regional daily Italian precipitation series. International Journal of Climatology, 543 - 558.

Bucchignani E., M. M. (2014). Regional climate simulations with COSMO-CLM over the Mediterranean area . Proceedings second annual conference Climate change: scenarios, impacts and policy. Venice.

Bucelli, P., & Costantini, E. (2006). Vite da vino e zonazioni vitivinicole. In Metodi di valutazione dei suoli e delle terre (p. 922). Siena: Edizioni Cantagalli.

Caffarra, A. &. (2010). Increasing the robustness of phenological models for Vitis vinifera cv. Chardonnay. International journal of biometeorology, 255 - 267.

Camarda, I., Laureti, L., Angelini, P., Capogrossi, R., Carta, L., & Brunu, A. (2015). Il Sistema Carta della Natura della Sardegna. ISPRA.

Canu, S., Rosati, L., Fiori, M., Motroni, A., Filigheddu, F., & Farris, E. (2014). Bioclimate map of Sardinia (Italy). Journal of Maps. doi:10.1080/17445647.2014.988187

Caterisano, R., Cirone, P., Maiolo, B., & Mariani, L. (2010). Aspetti agro-fenologici della vite nel crotonese e risultati della lotta a lobesia botrana (lepidoptera, tortricidae). 1. Cervia (RA): Giornate fitopatologiche.

Celette, F., Ripoche, A., & Gary, C. (2010). WaLIS-A simple model to simulate water partitioning in a crop association: the example of an intercropped vineyard. Agricultural water management, 97(11), 1749-1759.

Cesaraccio, C. S. (2004). Chilling and forcing model to predict bud-burst of crop and forest species. Agricultural and Forest Meteorology, 1 - 13.

Chiune, I., Garcia de Cortazar Atauri, I., Kramer, K., & Hänninen, H. (2013). Plant Development Models. In Phenology: An Integrative Environmental Science (p. 275-293). Dordrecht: Schwarz MD.

Chiune, I., Yiou, P., Viovy, N., Seguin, B., Daux, V., & Le Roy Ladurie, E. (2004). Grape ripening as a past climate indicator. Nature, 432, 289-290.

Chuine, I. (2000). A unified model for budburst of trees. Journal of theoretical biology, 337 - 347.

Clarke, L., Edmonds, J., Jacoby, H., Pitcher, H., Reilly, J., & Richels, R. (2007). Scenarios of greenhouse gas emissions and atmospheric concentrations. Washington DC: Sub-report 2.1a of Synthesis and Assessment Product 2.1. Climate Change Science Program and the Subcommittee on Global Change Research.

Cola, G., Mariani, L., Salinari, F., Civardi, S., Bernizzoni, F., Gatti, M., & Poni, S. (2014). Description and testing of a weather-based model for predicting phenology, canopy development and source-sink balance in Vitis vinifera L. cv Barbera. Agricultural and forest meteorology, 184, 117-136.

Confalonieri , R., Rosenmund, A., & Baruth, B. (2009). An improved model to simulate rice yield. Agronomy for sustainable Development. 29:463-474.

Convisar. (2012). Modelli viticoli e gestione del vigneto in Sardegna. (N. G., A cura di) Italia: © Convisar.

Cook, J., Nuccitelli, D., Green, S., Richardson, M., Winkler, B., Painting, R., . . . Skuce, A. (2013). Quantifying the consensus on anthropogenic global warming in the scientific literature. Environmental Research Letters, 8.

Cossu, A., Fronteddu, F., & Bodini, A. (2004). Indici bioclimatici e curva di maturazione di Cannonau. L’informatore Agrario(21), 61-63.

Cuccia, C., Bois, B., Richard, Y., Parker, A., Garcia de Cortazar-Atauri, I., Van Leeuwen, C., & Castel, T. (2014). Phenological model performance to warmer conditions: application to pinot noir in Burgundy. Journal International des Sciences de la vigne et du vin, 48, 169-178.

De Melo-Abreu, J. P. (2004). Modelling olive flowering date using chilling for dormancy release and thermal time. Agricultural and Forest Meteorology, 117 - 127.

Duchêne, E. H. (2010). The challenge of adapting grapevine varieties to climate change. . Climate research. 193.

Duchêne, E., & Schneider, C. (2005). Grapevine and climatic changes: a glance at the situation in Alsace. Agronomy for sustainable development, 25, 93-99.

Easterling, D. R. (2000). Observed variability and trends in extreme climate events: a brief review. Bulletin of the American Meteorological Society, 417 - 425.

Failla, O., Mariani, L., & Toninato, L. (2008). Viticoltura di territorio. In La vite e il vino (p. 624). Milano: Bayer CropScience.

FAO. (1976). Land suitability classifications. In A framework for land evaluation. Roma: Food and Agriculture Organization of the United Nations, Soils Bulletin 32.

FAO. (2015). Cliamte change and food systems: global assessments and implications for food security and trade. Food Agricolture Organization of the United Nations .

Fila, G., Gardiman, M., Belvini, P., Meggio, F., & Pitacco, A. (2014). A comparison of different modelling solution for studying grapevine phenology under present and future climate scenarios. Agricultural and Forest Meteorology, 195-196:192-205.

Fraga, H. M.-P. (2013). Future scenarios for viticultural zoning in Europe: ensemble projections and uncertainties. International journal of biometeorology, 909 - 925.

Fraga, H., Malheiro, A., Moutinho-Pereira, J., Jones, G., Alves, F., Pinto, J., & Santos, J. (2014). Very high-resolution bioclimatic zoning of Portuguese wine regions: present and future scenarios. Regional Environmental Change, 14, 295-306.

Fraga, H., Malheiro, A., Mutinho-Pereira, J., & Santos, J. (2012). An overview of climate change impacts on European viticulture. Food and Energy Security, 1(2), 94-110.

Fraga, H., Santos, J., Malheiro, A., Oliveira, A., Moutinho-Pereira, J., & Jones, G. (2015). Climatic suitability of Portuguese grapevine varieties and climate change adaptation. International journal of climatology.

Franco, L. (2014). Valutazione delle caratteristiche fenologiche e qualitative del nero d'avola nei diversi territori siciliani. Master Thesis.

Fujino, J., Nair, R., Kainuma, M., Masui, T., & Matsuoka, Y. (2006). Multigas mitigation analysis on stabilization scenarios using aim global model. Energy Journal(special 3), 343-354.

Garcia de Cortazar-Atauri, I. (2006). Adaptation du modèle STICS à la vigne (Vitis vinifera L.): utilisation dans le cadre d'une étude d'impact du changement climatique à l'échelle de la France. PhD Thesis.

Garcia de Cortázar-Atauri, I. G. (2010). A curvilinear process-based phenological model to study impacts of climate change on grapevine (Vitis vinifera L.). Proceedings of Agro 2010: the 11th ESA Congress (p. 907-908). Montpellier, France: Agropolis International Editions: Montpellier.

Garcia de Cortazar-Atauri, I., Brisson, N., & Gaudillere, J. (2009a). Performace of several model for predicting budburst date of grapevine (Vitis Vinifera L.). International journal of biometeorology, 53(4), 317-326.

Garcia de Crotazar-Atauri, I., Brisson, N., Ollat, N., Jacquet, O., & Payan, J. (2009b). Asynchronous dynamics of grapevine (Vitis vinifera) maturation: experimental study for a modelling approach. Journal internationales des sciences de la vigne e du vin, 43(2), 83-87.

Garnier, E., Daux, V., Yiou, P., & Garcia de Cortazar-Atauri, I. (2011). Grapevine harvest dates in Besançon (France) between 1525 and 1847: Social outcomes or climatic evidence? Climatic Change, 104, 703-727.

Gladstones, J. (1992). Viticulture and environment. Winetitles.

Godwin, D., White, R., Sommer, K., Walker, R., Goodwin, I., & Clingeleffer, P. (2002). VineLOGIC – a model of grapevine growth and development and water use. In Australian society of viticulture and oenology society (p. 46-50). Adelaide: C. Dundon, R. Hamilton, R. Johnstone and S.Partridge.

Gometz, P. (2005-2006). Confronto tra cloni di Cannonau, Grenache e Tocai allevati su cordoni mobilizzati. Sassari: Thesis. Univestià degli Studi di Sassari.

Gutierrez, A., Williams, D., & Kido, H. (1985). A model of grape growth and development: the mathematical structure and biological considerations. Crop science, 25(5), 721-728.

Hall, A. &. (2010). Spatial analysis of climate in wine grape-growing regions in Australia. Australian Journal of Grape and Wine Research, 389 - 404.

Hannah, L., Roehrdanz, P., Ikegami, M., Shepard, A., Shaw, M., Tabor, G., . . . Hijmans, R. (2013). Climate change, wine, and conservation. Proceedings of the National Academy of Sciences, 110(17), 6907-6912.

Hijioka, Y., Matsuoka, Y., Nishimoto, H., Masui, T., & Kainuma, M. (2008). Global GHG emission scenarios under GHG concentration stabilization targets. Journal of Global Environmental Engineering(13), 97-108.

Huglin, M. (1978). Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. Comptes rendus de l'académie d'agriculture de France, 64, 1117-1126.

Iglesias, A. G. (2012b). A regional comparison of the effects of climate change on agricultural crops in Europe. Climatic Change, 29 - 46.

Iglesias, A. Q. (2012a). From climate change impacts to the development of adaptation strategies: challenges for agriculture in Europe. Climatic Change, 143 - 168.

IPPC 2014. (s.d.). 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. IPCC,[Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva, Switzerland.

Irimia, L., Patriche, C., & Quénol, H. (2013). Viticultural zoning: A comparative study regarding the accuracy of different approaches in vineyards climate suitability assessment. Cercetari agronomice in Moldova, 46(3), 95-106.

Jones, G. (2007). Climate change: observations, projections, and general implications for viticulture and wine production. In Working paper n°7. Economics Department, Whitman College, USA.

Jones, G. V. (2006). Climate and terroir: Impacts of climate variability and change on wine. . Geoscience Canada reprint series: 203-217.

Jones, G. V. (2010). Spatial analysis of climate in winegrape growing regions in the western United States. American Journal of Enology and Viticulture, 313 - 326.

Jones, G., Reid, R., & Vilks, A. (2012). Climate, grapes, and wine: structure and suitability in a variable and changing climate. In The geography of wine: regions, terroir and techniques (p. 109-133).

Jones, G., White, M., Cooper, O., & Storchmann, K. (2005). Climate change and global wine quality. Climatic change, 73, 319-343.

Jones, J., Hoogenboom, G., Porter, C., Boote, K., Batchelor, W., Hunt, L., . . . Ritchie, J. (2003). The DSSAT cropping system model. European Journal of Agronomy, 235-265.

Kizildeniz, T. M. (2015). Effects of climate change including elevated CO 2 concentration, temperature and water deficit on growth, water status, and yield quality of grapevine (Vitis vinifera L.) cultivars. Agricultural Water Management, 155 - 164.

Klein Tank, A. M. (2003). Trends in indices of daily temperature and precipitation extremes in Europe. Journal of Climate, 3665 - 3680.

Koufos, G. M. (2014). Viticulture–climate relationships in Greece: the impacts of recent climate trends on harvest date variation. . International Journal of Climatology, 1445 - 1459.

Kroodsma, D. A. (2006). Carbon sequestration in california agriculture. Ecological Applications, 1975 - 1985.

Kubach, H. K. (2012). Wine Grape Suitability and Quality in a Changing Climate, An Assessment of Adams County, Pennsylvania (1950 – 2099). Tratto da (accessing date: 03.10.2014) http://www.ship.edu/uploadedfiles/ship/geo-ess/graduate/exams/kubach_answer_120502.pdf.

Laget, F., Tondut, J.-L., Deloire, A., & Kelly, M. (2008). Climate trends in a specific mediterranean viticultural area between 1950 and 2006. Journal International des Sciences de la Vigne et du Vin, 42, 113-123.

Le Roy Ladurie, E., Daux, V., & Luterbacher, J. (2006). Le climat de Bourgogne et d'ailleurs. Histoire,économie et société, 3, 421-436.

Lebon, E., Dumas, V., Pieri, P., & Schultz, H. (2003). Modelling the seasonal dynamics of the soil water balance of vineyards. Functional plant biology(30), 699-710.

Lobell, D., Field, C., Cahill, K., & Bonfils, C. (2006). Impacts of future climate change on California perennial crop yields: Model projections with cliamte and crop uncertainties. Agricultural and Forest Meteorology, 141, 208-218.

Lopez-Bustins, J. A. (2014). Global change and viticulture in the Mediterranean region: a case of study in north-eastern Spain. Spanish Journal of Agricultural Research, 78 - 88.

Lovicu, G., Farci, M., Sedda, M., Fadda, N., Melis, M., Sanna, F., & Pintore, R. (2011). Effect of rootstock and training system on Cannonau grape in South Sardinia. XXXIV OIV Symposium.

Malheiro, A., Santos, J., Fraga, H., & Pinto, J. (2010). Climate change scenarios applied to viticultural zoning in Europe. Climate research, 43, 163-177.

Mancosu, N. (2011/2012). Agricultural water demand assessment using the SIMETAW# model. PhD Thesis. Università degli Studi di Sassari.

Maracchi, G., Sirotenko, O., & Bindi, M. (2005). Impact of present and future cliamte variability on agriculture and forestry in temperate regions: Europe. Climatic Change, 70, 117-135.

McIntyre, G. N. (1982). The chronological classification of grapevine phenology. American Journal of Enology and Viticulture, 80 - 85.

Meehl, G. A. (2007). The WCRP CMIP3 multimodel dataset: A new era in climate change research. . Bulletin of the American Meteorological Society, 1383 - 1394.

Mereu, V. (2010). Climate change impact on durum wheat in Sardinia. PhD Thesis. Università di Sassari.

Mirza, M. (2011). Climate change, flooding in South Asia and implications. Regional Environmental Change, 95 - 107.

Moncur, M. W. (1989). Base temperatures for budbreak and leaf appearance of grapevines. American Journal of Enology and Viticulture, 21 - 26.

Moriondo, M. &. (2005). Cambiamenti climatici e ambiente vitivinicolo: impatto e strategie di adattamento. Rapporto finale per ARSIA.

Moriondo, M. &. (2007). Impact of climate change on the phenology of typical Mediterranean crops. Italian Journal of Agrometeorology, 5 - 12.

Moriondo, M., Ferrise, R., Trombi, G., Brilli, L., & Dibari, C. (2015). Modelling olive trees and grapevines in a changing climate. Environmental modelling & software (XXX), 1-15.

Moriondo, M., Jones, G., Bois, B., Dibari, C., Ferrise, R., Trombi, G., & Bindi, M. (2013). Projected shifts of wine regions in response to climate change. Climatic change, 119, 825-839.

Moriondo, M., Jones, G., Bois, B., Dibari, C., Ferrise, R., Trombi, G., & Bindi, M. (2013). Projected shifts of wine regions in response to climate change. Climatic change (119(3-4)), 825-839.

Nendel, C., & Kersebaum, K. (2004). A simple model approach to simulate nitrogen dynamics in vineyard soils. Ecological modelling, 177(1), 1-15.

Nieddu, G. (2011). Vitigni della Sardegna. Notizie storiche, distribuzione geografica, sinonimi. Cagliari: Convisar, Vino e Sardegna.

Nigond, J. (1967). Recherches sur la dormance des bourgeons de la vigne. Institut Nationale de la Recherche Agronomique.

OIV. (2015). Statistical report on World Vitiviniulture. Mainz, Germany: OIV.

Olesen, J., & Bindi, M. (2002). Consequences of climate change for European agricultural productivity, lnd use and policy. European Journal of Agronomy, 16, 239-262.

Olesen, J., Trnka, M., Kersebaum, K., Skjelvag, A., Seguin, B., Peltonen-Sainio, P., . . . Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. European Journal of Agronomy, 34, 96-112.

Oliveira, M. (1998). Calculation of budbreak and flowering base temperatures for Vitis vinifera cv. Touriga Francesa in the Douro Region of Portugal. American Journal of Enology and Viticulture, 74 - 78.

Pallas, B., Loi, C., Christophe, A., Cournède, P., & Lecoeur, J. (2011). Comparison of three approaches to model grapevine organogenesis in conditions of fluctuating temperature, solar radiation and soil water content. Annals of botany, 107(5), 729-745.

Palliotti, A. T. (2014). Changes in vineyard establishment and canopy management urged by earlier climate-related grape ripening: A review. Scientia Horticulturae, 43 - 54.

Palosuo, T., Kersebaum, K., & Angulo, C. (2011). Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models.

Parker, A. d.-A. (2013). Classification of varieties for their timing of flowering and veraison using a modelling approach: A case study for the grapevine species Vitis vinifera L. Agricultural and Forest Meteorology, 249-264.

Parker, A. K.-A. (2011). General phenological model to characterise the timing of flowering and veraison of Vitis vinifera L. Australian Journal of Grape and Wine Research,, 206 - 216.

Parra, C., Aguirreolea, J., Sánchez-Díaz, M., Irigoyen, J., & Morales, F. (2010). Effects of climate change scenarios on Tempranillo grapevine (Vitis vinifera L.) ripening: response to a combination of elevated CO2 and temperature, and moderate drought. Plant and soil, 337, 179-191.

Poni, S., Palliotti, A., & Bernizzoni, F. (2006). Calibration and evaluation of a STELLA software-based daily CO2 balance model in Vitis vinifera L. Journal of the American Society for Horticultural Science, 131(2), 273-283.

Porcu, S. (2004-2005). Valutazione delle caratteristiche agronomiche e qualitative di cloni di Vermentino selezionati in Sardegna e Corsica. Sassari: Thesis. Università degli Studi di Sassari.

Pouget, R. (1967). Méthode d'appréciation de l'évolution physiologique des bourgeons pendant la phase de pré-débourrement: application à l'étude comparée du débourrement de la Vigne. Vitis, 294 - 302.

Pouget, R. (1967). Méthode d'appréciation de l'évolution physiologique des bourgeons pendant la phase de pré-débourrement: application à l'étude comparée du débourrement de la Vigne. Vitis, 294 - 302.

Ramos, M., Jones, G., & Martínez-Casasnovas, J. (2008). Structure and trends in climate parameters affecting winegrape production in northeast Spain. Climatic Research, 38(1), 1-15.

Riahi, K., Grübler, A., & Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change(74), 887-935.

Riou, C. (1994). Le déterminisme climatique de la maturation du raisin : application au zonage de la teneur en sucre dans la Communauté Européenne . Luxembourg: Commission Européenne.

Ripoche, A., Rellier, J., Martin-Clouaire, R., Paré, N., Biarnès, A., & Gary, C. (2011). Modelling adaptive management of intercropping in vineyards to satisfy agronomic and environmental performances under Mediterranean climate. Environmental modelling and software, 26(12), 1467-1480.

Rochard, J., Clement, J., & Srhiyeri, A. (2006). The evolution of grape harvest dates in relation to climate change. Sixth International Cool Climate Symposium for Viticulture and Oenology. Christchurch, New Zealand.

Saladiè, O., Montse, N., Aguilar, E., & Lampreave, M. (2007). Variation de la date du début des vendanges en catalogne au cours de la période de la plus forte influence anthropique sur le climat. Climate and Viticulture, (p. 65-71). Zaragoza (Spain).

Santos, J., Malheiro, A., Karremann, M., & Pinto, J. (2011). Statistical modelling of grapevine yield in the Port Wine region under present and future climate conditions. International Journal of Biometeorology, 55, 119-131.

Santos, J., Malheiro, A., Pinto, J., & Jones, G. (2012). Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. Climate research, 51, 8-103.

Schultz, H., & Jones, G. (2010). Climate induced historic and future changes in viticulture. Journal of Wine Research, 21, 137-145.

Seguin, B., & Garcia de Cortazar, I. (2005). Climate warming: consequences for viticulture and notion of "terroirs" in Europe. Acta Horticulturae, 689.1:61-69.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsidding, E., . . . Tubiello, F. (2014). Agriculture,Forestry and Other Land Use (AFOLU). In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Smith, S., & Wigley, T. (2006). MultiGas forcing stabilization with minicam. Energy Journal(special 3), 373-392.

Soja, G., Zehetner, F., Rampazzo-Todorovic, G., Schildberger, B., Hackl, K., Hofmann, R., . . . Omann, I. (s.d.). Wine production under climate change conditions: mitigation and adaptation options from the vineyard to the sales booth. (p. 4-7). In 9th European IFSA Symposium.

Sotes, V. (2010). Historical zoning in the world. VIII International Terroir Congress (p. 3-9). Soave (VR)-Italy: Veneto Agricoltura - CRAVIT.

Spanna, F. S. (2005). Risultati preliminari dell'applicazione di un modello unificato per la simulazione del germogliamento di specie arboree spontanee. Convegno AIAM "Agrometeorologia. risorse naturali e sistemi di gestione del territorio", (p. 94 - 95). Vasto.

Stock, M. G. (2004). Reliability of climate change impact assessments for viticulture. VII International Symposium on Grapevine Physiology and Biotechnology , (p. 29-40).

Stockle, C., Donatelli, M., & Nelson, R. (2003). CropSyst, a cropping systems simulation model. European jurnal of agronomy, 18(3), 289-307.

Tomasi, D., Gaiotti, F., Locci, O., & Goddi, E. (2012). Le terre e le vigne del cannonau di jerzu. Agenzia Laore Sardegna.

Tomasi, D., Jones, G., Giust, M., Lovat, L., & Gaiotti, F. (2011). Grapevine Phenology and Climate Change: Relationships and Trends in the Veneto Region of Italy for 1964–2009. American Journal of Enology and Viticulture, 62(3), 329-339.

Tonietto, J. (1999). Les macroclimats viticoles mondiaux et l'influence du mésoclimat sur la typicité de la Syrah et du Muscat de Hambourg dans le sud de la France: méthodologie de caráctérisation. These Doctorat. Montpellier: Ecole Nationale Supérieure Agronomique.

Tonietto, J., & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. Agricultural and forest meteorology, 124(1), 81-97.

Tonietto, J., Sotés, V., Zanus, M., Montes, C., Uliarte, E., Antelo, L., . . . Carbonneau, A. (2010). L'effet du climat viticole sur la typicité des vins rouges- Caractérisation au niveau des régions viticoles Ibéro-Americaines. In VIII International Terroirs Congress (Vol. 3, p. 17-22). Soave, Italy: CRA-VIT Centro di Ricerca per la Viticoltura.

Ugalde, D. B. (2007). Implications of climate change for tillage practice in Australia. Soil and Tillage Research,, 318 - 330.

van der Linden, S., Leiserowitz, A., Feinberg, G., & Maibach, E. (2015). The Scientific Consensus on Climate Change as Gateway Belief: Experimental Evidence. PLoS ONE, doi:10.1371/journal.pone.0118489.

van Diepen, C., Wolf, J., & van Keulen, H. (1989). WOFOST: a simulation model of crop production. Soil Use and Management(5:16-24), 5:16-24.

van Leeuwen, C., Schultz, H., Garcia de Cortazar-Atauri, I., Duchêne, E., Ollat, N., Pieri, P., . . . Delrot, S. (2013). Why climate change will not dramatically decrease viticultural suitability in main wine-producing areas by 2050. Proceedings of the National Academy of Sciences, 110(33), E3051-E3052.

Van Vuuren, D., Den Elzen, M., Lucas, P., Eickhout, B., Strengers, B., Van Ruijven, B., . . . Van Houdt, R. (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies. Climatic Change(81), 119-159.

Van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., . . . Rose, S. (2011). The representative concentration pathways: an overview. Climatic change, 109(1-2), 5-31.

Van Vuuren, D., Eickhout, B., Lucas, P., & Den Elzen, M. (2006). Long-termmulti-gas scenarios to stabilise radiative forcing—exploring costs and benefits within an integrated assessment framework. Energy Journal (27), 201-233.

Vaudour, E. (2002). The quality of grapes and wine in relation to geography: notions of terroir at various scales. Journal of Wine Research, 13, 117-141.

Vaudour, E. (2003). Les terroirs viticoles. Définitions, caractérisation, protection. Dunod, Paris.

Vuković, A., Vujadinović, M., Djurdjević, V., Ranković-Vasić, Z., Marković, N., Atanacković, Z., . . . Petrović, N. (2010). Appliance of climate projections for climate change study in serbian vineyard regions. In VIII International Terroirs Congress (Vol. 3, p. 36-41). Soave, Italy: CRA-VIT Centro di Ricerca per la Viticoltura.

Watkins, R., Meyer, V., & Assoc. (1997). Vineyard site suitability in Eastern California. GeoJournal, 43(3), 229-239.

Webb, L. B. (2011). Observed trends in winegrape maturity in Australia. Global Change Biology, 2707 - 2719.

Webb, L., Whetton, P., & Barlow, E. (2007). Modelled impact of future climate change on the phenology of wingrapes in Australia. Australian Journal of Grape and Wine Research (13), 165-175.

Webb, L., Whetton, P., & Barlow, W. (2008). Climate change and wine grape quality in Australia. Climate research, 36, 99-111.

Wermelinger, B., Baumgartner, J., & Gutierrez, A. (1991). A demographic model of assimilation and allocation of carbon and nitrogen in grapevines. Ecological modelling, 53, 1-26.

Williams, D. W. (1985). Validation of a model for the growth and development of the Thompson Seedless grapevine. II. Phenology. American Journal of Enology and Viticulture,, 283 - 289.

Winkler, A., Cook, J., Kliwer, W., & Lider, L. (1974). General viticolture. Berkeley: University of California Press.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., . . . Edmonds, J. (2009). Implications of limiting CO2 concentrations for land use and energy. Science(324), 1183-1186.

Wolfe, D., Schwartz, M., Lakso, A., Otsuki, Y., Pool, R., & Shaulis, N. (2005). Climate change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. International Journal of Biometeorology, 49, 303-309.

Wreford, A., Moran, D., & Adger, N. (2010). Climate change and agriculture: impact, adaptation and mitigation. PAris: OECD Publishing. doi:http://dx.doi.org/10.1787/9789264086876-en

Yiou, P., García de Cortázar-Atauri, I., Chiune, I., Daux, V., Garnier, E., Viovy, N., . . . Boursiquot, J.-M. (2012). Continental atmospheric circulation over Europe during the Little Ice Age inferred from grape harvest dates. Climate of the Past, 8, 577-588.

ANNEX

ANNEX I

Table 3.1: dataset available for each variety

N° obs	*Varieties*											
	CABERNET F.	CABERNET S.	CANNONAU	CHARDONNAY	MERLOT	NERO D'AVOLA	WHITE PINOT	PROSECCO	RENAN RIESLING	SANGIOVESE	SAUVIGNON	VERMENTINO
start BB	12	10	27	10	10	-	11	-	11	13	11	20
50% BB	12	17	43	10	23	17	18	17	12	12	12	21
start FLO	10	14	32	12	12	-	11	17	12	14	12	20
50% FLO	10	17	48	12	23	17	18	17	11	15	11	20
end FLO	-	1	8	-	-	-	-	-	-	-	-	12
start VER	9	10	32	10	22	-	10	17	10	14	10	19
50% VER	9	17	40	10	10	17	16	17	10	10	10	7
end VER	-	-	8	-	-	-	-	-	-	-	-	12

Table 3.2: Phenagri database

	LATINA	*S.APOLLINARE (PG)*	*SPRESIANO (TV)*	*TENUTA CANNONA (AL)*	*VILLASOR (CA)*	*N° obs*							
						Start BB	50% BB	Start FLO	50% FLO	End FLO	Start VER	50% VER	End VER
CABERNET F.	may 1997 – aug 1998	apr 1997 – aug 1999	apr 1997 – aug 1999	apr 1998 – aug 1999	apr 1998 – aug 1998	12	12	10	10	-	9	9	-
CABERNET S.	may 1997 - aug 1999	apr 1997 – aug 1999	apr 1997 – aug 1999	apr 1998 – aug 1999	apr 1998 – aug 1998	10	12	12	11	-	10	10	-
CANNONAU	-	-	apr 1997 – aug 1999	-	apr 1998 – jul 1999	5	5	4	4	-	4	4	-
CHARDONNAY	may 1997 – jul 1999	mar 1997 – aug 1999	mar 1997 – aug 1999	mar 1998 – jul 1999	mar 1998 – jul 1999	10	10	12	12	-	10	10	-
MERLOT	may 1997 – aug 1999	apr 1997 – aug 1999	apr 1997 – aug 1999	apr 1998 – aug 1999	apr 1998 – jul 1999	10	11	12	11	-	10	10	-
PINOT BIANCO	may 1997 – jul 1999	apr 1997 – aug 1999	apr 1997 – aug 1999	Mar 1998 – aug 1999	mar 1998 – jul 1999	11	12	11	12	-	10	10	-
RIESLING RENANO	may 1997 – aug 1999	apr 1997 – aug 1999	apr 1997 – aug 1999	mar 1998 – aug 1999	mar 1998 – jul 1999	11	12	12	11	-	10	10	-
SANGIOVESE	may 1997 – aug 1999	apr 1997 – aug 1999	apr 1997 – aug 1999	mar 1998 – aug 1999	mar 1998 – jul 1999	11	12	12	11	-	10	10	-
SAUVIGNON	may 1997 – aug 1999	apr 1997 – aug 1999	apr 1997 – aug 1999	mar 1998 – aug 1999	mar 1998 – jul 1999	11	12	12	11	-	10	10	-
VERMENTINO	giu 1997 – aug 1999	apr 1997 – aug 1999	apr 1997 – aug 1999	-	apr 1998 – aug 1998	9	10	9	9	1	8	7	1

Table 3.3: Zoning dataset

Region	*Site*	*Varieties*		
		CABERNET SAUVIGNON	WHITE PINOT	CANNONAU
Veneto	Lonigo	2000-2002		
Zonazione Vitivinicola Colli Berici	Grancona	2000-2002		
	Barbarano	2000-2002		2000-2002
	Cognola			2000-2002
	Alonte		2000-2002	
	Sarego		2000-2002	
Sardinia	Sa Canna fondovalle			2004-2006
Zonazione Vitivinicola del Cannonau di Jerzu	Sa Canna versanti bassi			2004-2006
	Sa Canna versanti alti			2004-2006
	Flumini			2004-2006
	PELAUMANNUPELAEDDU fondovalle			2004-2006
	PELAUMANNUPELAEDDU versanti			2004-2006
	Pardu			2004-2006
N°obs	start BB	-	-	14
	50% BB	3	3	20
	start FLO	-	-	20
	50% FLO	3	3	26
	end FLO	-	-	-
	start VER	-	-	20
	50% VER	3	3	26

Table 3.4: PRIN dataset

Region	*Site*	*Varieties*			
		CABERNET S.	NERO D'AVOLA	PROSECCO	SANGIOVESE
Tuscany	Mortelle	2008-2009			2008
	Donna Olimpia	2008-2009			
	Brolio				2008
Sicily	Sambuca		2011-2013		
	Acate		2011-2013		
	Noto		2011-2013		
	Camporeale		2002-2003		
	Marsala		2003-2006		
Veneto	Istrana			1992-2008	
N° obs	start BB	-	-	-	2
	50% BB	2	17	17	-
	start FLO	2	-	17	2
	50% FLO	3	17	17	4
	end FLO	1	-	-	-
	start VER	-	-	17	4
	50% VER	4	17	17	-
	end VER	-	-	-	-

Table 3.5: PEP725 dataset

Region	*Site*	*Varieties*
		MERLOT
Trentino	Volano	1987-2006
N° obs	start BB	-
	50% BB	12
	start FLO	-
	50% FLO	12
	end FLO	-
	start VER	12
	50% VER	-
	end VER	-

Table 3.6: AA.VV. dataset: * *Gometz, 2005-2006; ** Cossu, et al., 2004; *** Porcu, 2004-2005: " " Uniss-DESA*

Region	*Site*	*Varieties*	
		CANNONAU	VERMENTINO
Sardinia	Alghero	2005-2006*	1999-2002
	Siniscola	2000-2003**	
	Oristano		2000-2003/2005 2004-2005***
N° obs	start BB	8	11
	50% BB	12	11
	start FLO	8	11
	50% FLO	12	11
	end FLO	8	11
	start VER	8	11
	50% VER	4	-
	end VER	8	11

Table 3.7: The meteorological dataset collected for each site, the referenced period and the original source.

Region	*Station*	*Altitude and coordinates*	*Year of observations*	*Source*
Piemont	*Novi Ligure*	*200 m.a.m.s.l.* *44°46'51.17"N* *8°47'18.26"E*	*1997-1999*	*www.tutiempo.it*
Trentino Alto Adige	*Paganella*	*2129 m.a.m.s.l.* *46°08'38.31"N* *11°02'16.08"E*	*1987-2006*	*www.tutiempo.it*
Veneto	*Treviso S.Angelo*	*23 m.a.m.s.l.* *45°39'06.22"N* *12°12'00.97"E*	*1997-1999*	*www.tutiempo.it*
	Treviso Istrana	*41 m.a.m.s.l.* *45°41'19.17"* *N12°06'04.69"E*	*1992-2008*	*www.tutiempo.it*
	Vicenza Airport	*53 m.a.m.s.l.* *45°34'17.16"N* *11°31'50.28"E*	*1999-2002*	*www.tutiempo.it*
Umbria	*Perugia*	*205 m.a.m.s.l.* *43°05'32.99"N* *12°30'17.01"E*	*1997-1999*	*www.tutiempo.it*
Lazio	*Latina*	*26 m.a.m.s.l.* *41°32'44.22"* *N12°54'34.46"E*	*1997-1999*	*www.tutiempo.it*
Sardinia	*Alghero airport*	*23 m.a.m.s.l.* *40°38'22.74"N* *8°17'33.12"E*	*1998-2006*	*www.tutiempo.it*
	Siniscola	*14 m.a.m.s.l.*	*2000-2003*	*SAR Sardegna*

		40° 35' 41.321" N *9° 43' 37.156" E*		
	Oristano - Zeddiani	*14 m.a.m.s.l.* *39°58’ N 8°37’E*	*2000-2005*	*UCEA*
	Jerzu	*46 m.a.m.s.l.* *39° 47' 28.983" N* *9° 36' 20.189" E*	*2003-2006*	*SAR Sardegna*
	Cagliari airport	*28 m.a.m.s.l..* *39°20'38.28"N* *8°58'14.52"E*	*1997-1999*	*www.sias.regione.sicilia.it*
Sicily	*Sciacca*	*90 m.a.m.s.l..* *37° 35' 28,6382"N* *13° 02' 23,4641"E*	*2011-2013*	*www.sias.regione.sicilia.it*
	Acate	*60 m.a.m.s.l..* *36° 58' 28,2971"N* *14° 24' 03,0775"E*	*2011-2013*	*www.sias.regione.sicilia.it*
	Pachino	*50 m.a.m.s.l..* *36° 40' 54,7574"N* *15° 05' 42,9594"E*	*2011-2013*	*www.sias.regione.sicilia.it*
	Camporeale	*460 m.a.m.s.l..* *37° 54' 16,6301"N* *13° 06' 03,6766" E*	*2002-2003*	*www.sias.regione.sicilia.it*
	Marsala	*120 m.a.m.s.l..* *37° 48' 04,3196" N* *12° 34' 08,8447" E*	*2003-2006*	*www.sias.regione.sicilia.it*