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Mapping the Impacts of Climate Change on Mediterranean Viticulture

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Mapping the Impacts of Climate Change on Mediterranean Viticulture

A Senior Thesis by Zoë Knauss

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Abstract

Climate change will have a profound impact on viticulture across the planet in the coming decades. Viticulture in the Mediterranean Basin will be disproportionately affected, as it is considered a climate change hotspot. This study focuses on how the vineyards of three notable wine regions in southern France will be affected by projected changes in average annual temperature, total annual precipitation, average length of droughts, and average volumetric soil water (VSW) content in layer 1 soils due to climate change. Vineyard soils will also be affected by climate change in this region, indirectly impacting grape cultivation as well. A GIS approach was taken to display the difference in these climate variables on southern French vineyards between 2020 and 2050. Raster and vector datafiles from the Copernicus Land Monitoring Service and the Copernicus Climate Change Service were used under two French climate projection models and the RCP 4.5 climate scenario. The results of this GIS comparison indicated an increase in average annual temperature and average length of dry spells, a decrease in total annual precipitation, and relatively similar average VSW content on southern French vineyards by 2050. Grapes in this region will likely experience a decrease in desired flavors and other specific qualities for wine-production largely due to a shift in grapevine phenology driven by warmer temperatures throughout the growing season. Vineyards are also likely to yield a smaller quantity of usable wine grapes at harvest due to water stress. The stability, and even increase, in VSW content despite less precipitation and longer droughts indicates that there may be other facets of climate change that will impact soil moisture and, thus, viticulture in the future. There are strategies that can be used to mitigate the effects of climate change on viticulture and winemaking, including agricultural approaches and the blending of introduced resistant grape varieties with traditionally grown varieties to maintain quality and quantity.

Introduction

As climate change continues to affect the planet, many aspects of both the natural and human-inhabited world will be impacted. Agriculture is a sector that combines these two realms, as nature is manipulated for the benefit of human beings. One of the most sensitive forms of agriculture to climate change is viticulture, the cultivation of the grape species *Vitis vinifera* for the production of wine. Viticulture is present all around the world, with different regions suitable for the cultivation of specific grape varieties, thereby producing unique and delicious wines defined by their environment.

This study will focus on the ways climate change will specifically affect Mediterranean viticulture in the future. The following three wine regions in southern France will be studied: Languedoc-Roussillon, Provence, and the Rhone Valley. Please refer to Figure 1 below to see where these vineyards are located. The Languedoc-Roussillon region includes the most western vineyards, north of Spain. It is the largest wine region in France, with 201,500 hectares of grape-growing surface and 17,423 vineyards (Alonso Ugaglia et al. 2019). The Rhone Valley is located in the central portion of southern France, along both sides of the Rhone River (runs north/south between Nimes and Avignon). The Provence region includes the vineyards on the easternmost area of the map, around Marseille, Aix-en-Provence, and Toulon. The most commonly grown *Vitis vinifera* varieties in these three regions include Syrah, Grenache, Mourvèdre, and Carignan. These varieties thrive in the warmer, Mediterranean climate of southern France.

Figure 1.) Vineyards in the Languedoc-Roussillon, Provence, and Rhone Valley Regions

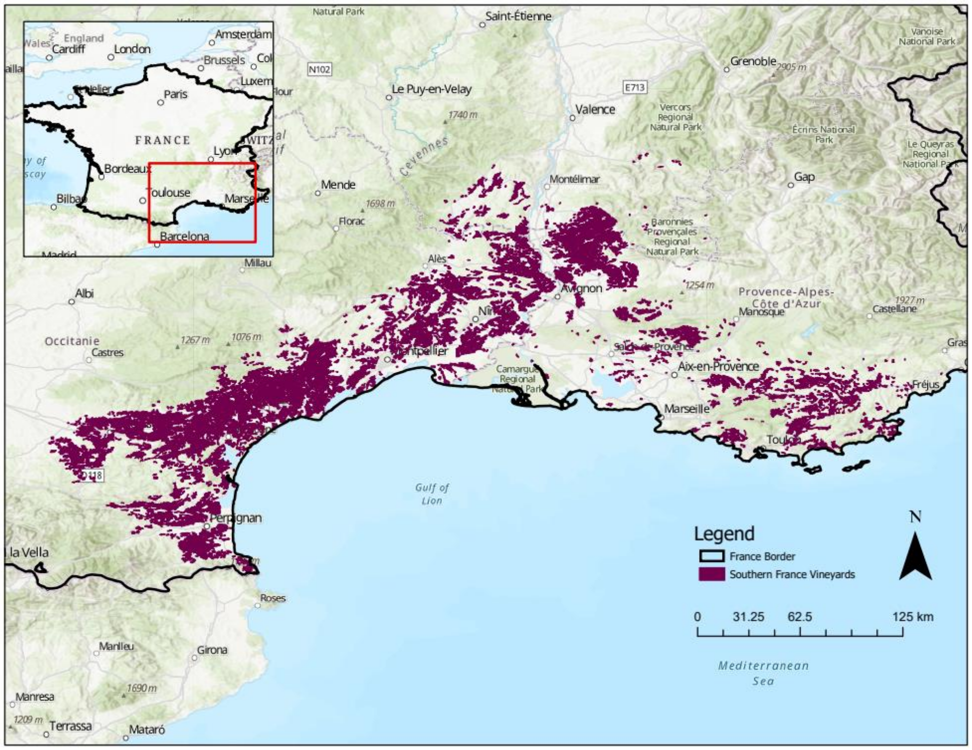


Figure 1. All vineyards in the Languedoc-Roussillon, Rhone Valley, and Provence wine-producing regions in the south of France. Small map in upper corner indicates the extent of France this location covers.

Downscaled climate projections for this region were displayed using geographic information systems (GIS). These projections were based on two French models and the RCP 4.5 experiment for the year 2050. The following climate variables were projected in the south of France in 2050: average annual temperature, total annual precipitation, average length of dry spells, and average volumetric soil water (VSW) content in layer 1 soils. These climate variables were also displayed for the year 2020. The vineyard areas making up the three wine regions of interest were overlaid with these climate variables in 2020 as well as their projections in 2050, to show how much each will change on vineyard areas over the 30-year period. A map of soils present in the south of France was also created using GIS, based on data from the European Soil Database. The purpose of this map is to provide a reference for the ways in which climate change not only directly impacts viticulture, but also impacts the soil, thereby indirectly affecting viticulture as well.

It was found that there will be an increase in average annual temperature and length of dry spells on southern French vineyards between 2020 and 2050. The total amount of annual precipitation will decrease within that period. The VSW content of soils in the region will remain relatively similar in 2050 as it was in 2020. Each of these shifts in climate will influence a specific aspect of viticulture, most profoundly affecting grape quality and quantity of grapes yielded. It was also found that these climate variables affect soil erosion, soil temperature, and soil nutrient availability, which will affect many aspects of viticulture as well.

Background

The Basics of Viticulture

The Mediterranean Region is known for its variety of unique ecosystems and rich cultures. One of the most famous aspects of this iconic area happens to be a product of both of these characteristics: wine. Wine has played an enormous role in Mediterranean society for thousands of years in many ways. Although wine grapes were initially discovered to exist around 6000 BC in the region between the Black and Caspian seas in eastern Europe, they have since spread to many other regions of the world thanks to humans (Chambers and Pretorius 2010). The earliest wine grape growing practices were not based on biological knowledge or science at all, but rather cultural experimentation and simply put, serendipity (Chambers and Pretorius 2010). However, winemaking has progressed over thousands of years into an extremely important global industry with a total area under vines of approximately 7.3 million hectares (Karlsson) and global market size of approximately 340 billion USD in 2020 (Fortune Business Insights).

The agricultural element of winemaking is referred to as viticulture, which includes cultivation of grapes for the production of wine. Viticulture requires specific climatic conditions and soil types, which makes grapes a very interesting plant to study from an ecological and geographic perspective. The Mediterranean Basin is generally regarded as the most well-known and best wine producing region in the world, as its ideal environmental conditions for viticulture have allowed it to develop a longstanding history of tradition and cultural significance surrounding wine. The French word *terroir* is frequently used in viticulture, as it refers to the combination of climate, soil, geography, and history of a location that affects the cultivation of a specific product (Deloire 2008). Although it is surely a scientific concept, *terroir* also signifies the heritage, tradition, and cultural value of the land, which is widely believed to affect grapes, and eventually wines, more significantly than other agricultural products (Deloire 2008). There is no true definition of terroir, but it is a critical concept in viticulture, especially in the Mediterranean region, where its traditions run deepest. Mapping *terroir* presents a large challenge, as it is a very subjective matter. Researchers have attempted to quantify *terroir* using the following equation: “basic terroir unit = ‘mesoclimate x soil / substratum’ for a series of years / vintages (Deloire 2008),” but there are also multiple other strategies for determining the terroir of a region in terms of viticulture. It is important to note that all of them depend heavily upon the environmental variables of climate, topography, and soil.

Regarding wine grapes themselves, *Vitis vinifera* is the only dominant species of wine grape that is native to Europe (Steinkraus 2009). There are two sub-species of *Vitis vinifera* which include *Vitis vinifera* subsp. *sylvestris* and *Vitis vinifera* subsp. *vinifera*. *V. vinifera* subsp. *sylvestris* is the undomesticated version of the grape and *V. vinifera* subsp. *vinifera* is the agricultural form of the grape (OIV (2017)). Most commonly known wine grapes are a cultivar (cultivated variety) of *Vitis vinifera* (Steinkraus 2009). *Vitis labrusca* and the lesser known *Vitis rotundifolia* are two other cultivated wine grape species that are native to the United States and are frequently cross-bred with Vitis vinifera to create a hybrid grape more resistant to cold climates and yield a product more similar to its European counterparts (Steinkraus 2009). Thousands of varieties of V*itis vinifera* exist, including the many well-known grapes such as Chardonnay, Sauvignon Blanc, Cabernet Sauvignon, Pinot Noir, Merlot, Grenache, and Syrah.

Another important distinction in viticulture is the Old World versus the New World. The Old World consists of the European countries in which wine-making was born thousands of years ago, including Austria, Bulgaria, France, Germany, Greece, Hungary, Italy, Portugal, Romania, Spain, and Switzerland. The New World consists of all the other wine-making regions that exist on the planet outside of Europe, which have emerged relatively recently, including Argentina, Australia, Brazil, Canada, Chile, Mexico, New Zealand, Peru, South Africa, the United States, and Uruguay. There are many distinct differences between the viticultural practices and wines themselves between the Old and New World. Terroir is one of the most important of these differences, as European climate and soil are unique from any other location on Earth. Additionally, wine is a much more integral part of Old World nations' history, culture, and identity than it is in New World nations. Although there has been increased collaboration between Old World and New World nations in terms of viticulture and winemaking, especially between the United States and European nations, it is important to acknowledge the fundamental environmental differences and viticultural practices between the Old and the New World that affect the cultivated grapes and wine produced (Aleixandre et al. 2016).

Current and Projected Climate of the Mediterranean Region

Although the Old World encompasses all European countries that produce wine, there are specific regions within it that experience different climates and environmental characteristics. The coastal land surrounding the Mediterranean Sea is referred to as the Mediterranean Basin, which includes portions of Spain, France, Italy, and Greece. This land is part of the Mediterranean Chaparral biome, which is also known as the "maquis". Chaparral biomes exist in only four other regions of the world outside of the Mediterranean Basin, including California, southwestern Australia, the Cape Region of South Africa, and central Chile, and it is no coincidence that these are also important regions for viticulture and wine production (Rundel et al. 2016). Chaparral biomes are characterized by their unique climate pattern of very hot, dry summers and mild, wet winters (Rundel, Arroyo et al. 2016). This seasonal climate fluctuation is the reason for the Mediterranean Basin’s unique terrestrial biodiversity and soils. For example, the variation in climate affects soil properties, as they are constantly gaining or losing moisture, key nutrients, and other elements due to the change in temperature and precipitation. Plant species diversity and growth depends heavily on this fluctuation, and *Vitis vinifera* is one native Mediterranean species that thrives on this climate and soil type.

Although climate change is a global phenomenon, there are certain regions on Earth that experience more severe impacts, which are known as “climate change hotspots (Ali et al. 2022).” According to the IPCC 6th Assessment Report, the Mediterranean Basin is considered one of these high-risk areas. Studies show that patterns in seasonal Mediterranean temperatures and precipitation have been shifting more noticeably than other regions of the world throughout the 20th Century due to climate change (Xoplaki et al. 2003). For example, there have been relatively frequent extended heat waves and droughts in the Mediterranean, which are likely to continue and increase throughout the 21st century. The Mediterranean basin’s geographic location is the primary reason why it is especially affected by climate change. It is located in a “transitional zone” between the arid North African deserts and temperate Central and Northern European region. This positioning allows for exposure to South Asian summer monsoons, the winter Siberian High-Pressure System, southern El Nino oscillations and northern Atlantic oscillations (Xoplaki, González-Rouco et al. 2003). These climate mechanisms drive the significant variability between Mediterranean summer and winter climates, as well as the variability in climate across the Mediterranean Basin spatially.

The combination of these climate mechanisms in the Mediterranean Basin and the persisting increase in global greenhouse gas emissions are driving changes in atmospheric temperature and occurrences of temperature extremes. This trend has caused widespread increases in the intensity, frequency, and duration of warm extremes as well as a decline in consistent colder temperatures and milder cold extremes. In the Mediterranean Basin, there has been an annual warming trend between the years of 1901 and 1998 of 0.75 degrees Celsius. The period between 1969 and 1998 was shown to experience more significant and intense warming. It was found that there has been a warming of approximately 0.05 degrees Celsius per decade in the Mediterranean throughout the 20th Century (Xoplaki, González-Rouco et al. 2003). Additionally, there has been an increase in summer temperature of 0.5 degrees Celsius between 1901 and 1999. In 2021, Europe experienced the warmest summer to date, which was measured to be 1.0° C above the summer average for 1991–2020 (ESA 2022). One study has modeled the future temperature increase in the Mediterranean region, stating that by the middle of the 21st Century, mean annual maximum temperatures may increase by 1.5 degrees Celsius (Goubanova and Li 2007). They are projected to increase by 3.2 degrees Celsius by the end of the 21st Century (Goubanova and Li 2007). There will also be an increase in annual minimum temperature that is comparable to the changes in maximum annual temperature throughout the 21st century.

Although annual precipitation has varied year to year in Europe since 1950, it is likely that the intensity and frequency of both droughts and floods will increase due to climate change in the future. Researchers have predicted that there will be a decrease in annual precipitation in the Mediterranean in winter, spring, and summer, but an increase in precipitation extremes in winter, spring, and autumn in the coming century (Goubanova and Li 2007). It is more difficult to predict patterns in future precipitation, as there are more environmental factors involved in precipitation events, but it is with certainty that we can state there will be notable changes in the future, which will greatly affect ecosystems and agriculture.

Variability of Soils in the Mediterranean

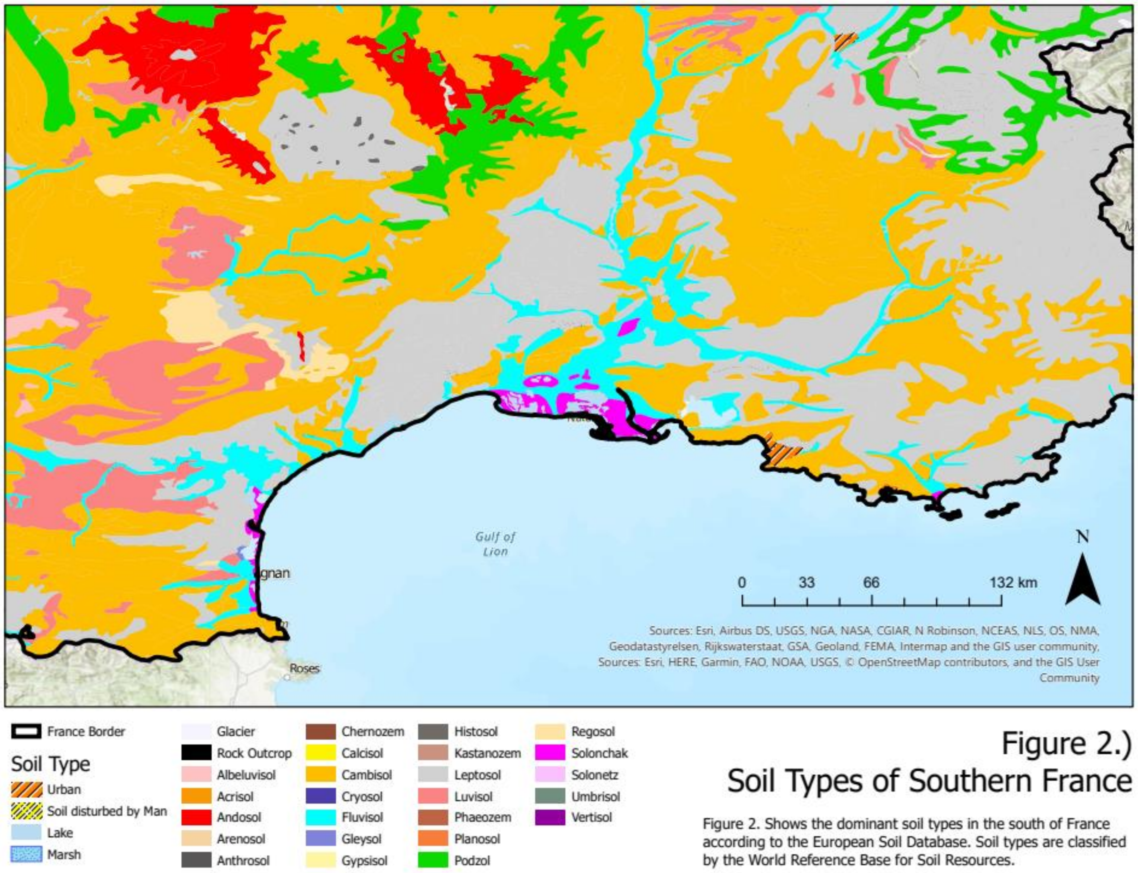
Mediterranean soils are not commonly found across the globe outside of regions characterized by a Mediterranean climate and Chaparral biome type. These regions include the Mediterranean Basin, California, Chile, the Western Cape Province of South Africa, and West and South Australia (Verheye 2005). The area surrounding the Mediterranean Sea is the largest region in which Mediterranean soils can be found, stretching over 22 countries that border the sea, as well as a few that are non-coastal but still considered Mediterranean (Zdruli, Kapur et al. 2010).

Soil formation and weathering occurs at the highest rate during the cool, wet winter months in the Mediterranean, as frequent precipitation allows for elements of the soil to move and leach out. There is also lower evapotranspiration due to lower temperatures which allows for shifts to occur within the soil (Verheye 2005). During the summer, a different set of chemical processes occur within the soil, changing its composition temporarily. As a result, Mediterranean soils are commonly classified in the “Xeric” soil moisture regime. Xeric soils are typically very low in moisture for approximately 45 or more days in the time period after the summer solstice, June 21. The average temperature of xeric soils over the course of a year is lower than 22 degrees Celsius, during which the temperature may differ more than 6 degrees Celsius between summer and winter months. These measurements are based on soils at a maximum depth of 50 centimeters (Soil Survey Staff 1999).

There is an extremely wide diversity of Mediterranean soils within this classification that are differentiated due to variations in climate, landscape, vegetation, parent material, and anthropogenic activity (Verheye 2005, Zdruli et al. 2010). The Mediterranean Basin is especially known for its famous “Terra Rossa,” which is a general term referring to the dry reddish soil that occurs throughout the region. However, there is confusion surrounding Terra Rossa, as it scientifically refers to the resulting soil of a specific chemical weathering process, although many regard it as an overarching, non-specific soil categorization for the region (Verheye 2005). It is necessary to differentiate soils that may all be considered “Terra Rossa” based on their individual characteristics and properties to understand how they affect an ecosystem or are themselves affected, rather than to group them all into one category solely based on their appearance.

Mediterranean soils develop due to various processes that break down the rock present in the region. These rocks are considered the parent material of soils in the Mediterranean basin. Dominant parent materials include calcareous sedimentary rocks such as limestone, dolomites, and to a lesser extent, marl (Verheye 2005). The physical and chemical properties of parent material, as well as the way in which it was weathered play a large role in the soil characteristics of soil it yields. Coherence, hardness, permeability, water infiltration, time, topography, biological activity, anthropogenic activity are all aspects of the parent material and weathering process that affect the rate at which parent material becomes a specific type of soil (Verheye 2005).

The resulting soils are categorized according to the World Reference Base for Soil Resources. In the Mediterranean Basin, soils are differentiated based on the pedo-climatic conditions in which they exist, such as soil temperature and moisture. The most dominant soil types in the Mediterranean Basin are Cambisols, Calcisols, Leptosols, and Luvisols (Allam et al. 2020). However, there are numerous other soils present at lesser extents, such as histosols, anthrosols, vertisols, fluvisols, andosols, and many more, which occupy specific ecosystems such as volcanic areas, deltas, alluvial basins, and lacustrine or marine environments. Please refer to Figure 2 below, showing the soils present in the south of France that will be of importance for the analytic portion of this thesis.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 2.)
Soil Types of Southern France

Figure 2. Shows the dominant soil types in the south of France according to the European Soil Database. Soil types are classified by the World Reference Base for Soil Resources.

Cambisols are the most widespread Mediterranean soil types. According to the Harmonized World Soil Database, they account for 26% of the total soil in the region (Allam et al. 2020). These soils span many different climatic areas present in the European Mediterranean countries, such as France, Italy, Spain, Portugal, Croatia, Bosnia-Herzegovina, Montenegro, Albania, Greece, Turkey and Cyprus (Zdruli, Kapur et al. 2010). They have moderate to deep soil profiles, containing evidence of weathered parent material and a lack of significant amounts of accumulated clay, organic matter, aluminum or iron compounds (Verheye 2005). They are widely regarded as some of the most productive soils on earth, as they are very ideal for agriculture (Allam, Moussa et al. 2020). Indigenous agro-ecosystems of southern Europe, such as those containing carobs, figs, olives, and grapes, tend to thrive on cambisols in naturally wetter or well-irrigated areas (Zdruli, Kapur et al. 2010).

Calcisols make up the second most widespread soils in the Mediterranean Basin, accounting for 22% of the total soil area (Allam et al. 2020). They are primarily found in the Northern Mediterranean Basin and used for grazing, agriculture, and forestry (Zdruli, Kapur et al. 2010). Because of frequent calcium carbonate translocation from the surface, calcisols are characterized by a layer of either soft, powdery or hard accumulation in a lower layer. In replacement, they have an ochric surface horizon (Verheye 2005). Calcisols have a good water holding capacity, which allows them to support a wide range of vegetable crops and when irrigated properly. On the other hand, their water holding capacity allows them to be very drought resistant (Allam, Moussa et al. 2020).

Leptosols are the third most widespread soil in the Mediterranean, making up 20% of the total soil area in the region (Allam et al. 2020). Leptosols are typically very shallow, due to their frequent presence on steep mountain slopes, mostly in the Northern Mediterranean Basin. Although they are high in mineral content, making them useful for grazing, agriculture, and forestry in mountainous areas, they are also extremely susceptible to erosion (Zdruli, Kapur et al. 2010, Allam, Moussa et al. 2020). As a result, terracing was employed as a strategy to minimize erosion and has since become an iconic and traditional Mediterranean landscape feature (Zdruli, Kapur et al. 2010). Terracing has allowed leptosols to become suitable soils for the cultivation of many indigenous Mediterranean crops, such as olives, grapes and other cereals (Zdruli, Kapur et al. 2010).

Luvisols are the fourth most widespread soil type in the Mediterranean region as they account for 10% of the total soil area (Allam et al. 2020). These soils occur on flat or slightly sloping land, mostly located in Portugal, Spain, France, Italy, Greece, Albania, Croatia, Turkey and Cyprus (Verheye 2005, (Zdruli, Kapur et al. 2010). Luvisols are characterized by high clay content, with illuviation transferring surface silicate clay to lower levels where they accumulate (Verheye 2005). Additionally, luvisols have an important nutrient content that makes them ideal for a wide range of agricultural uses (Zdruli, Kapur et al. 2010). Like leptosols, they require some terracing to prevent erosion when present on sloping lands. In these areas, fertile luvisols are suitable for fruit trees, olives, grazing, and very high quality viticulture, especially in central and northern Italy (Zdruli, Kapur et al. 2010).

Overall, Mediterranean soils range broadly in their characteristics, allowing for the region to support many different types of vegetation and agriculture. Unfortunately, climate change is causing an overall deterioration in the quality of these soils, making research and soil conservation a top priority for many groups (Verheye 2005). Increased erosion and salinization as well as decreased carbon and organic matter content in soil are some effects of climate change on these soils, which are driving policies to be developed to preserve Mediterranean soil quality and push for more sustainable land use practices for the future (Verheye 2005).

Climatic Constraints on Viticulture

Although all agriculture is affected to some degree by the climate, viticulture is arguably one of the most sensitive agricultural fields to weather patterns, temperature, and precipitation. Wine grape varieties are each affected slightly differently by these factors and thus provide a good case study for examining the effects of climate change on cultivated species. Additionally, the concentration of viticulture in the Mediterranean region, which is considered a climate change hotspot, is affected to an even greater extent than other New World wine-producing regions. Terroir is most highly affected by climatic temperature and moisture regimes, which substantially affect vine development, length of growing season, grape quality, grape yields and which grape varieties are suitable for the region.

The temperature of the region most heavily affects vine development, including the flowering, maturity, and harvest stages. As the Mediterranean experiences warmer and warmer mean annual temperatures, these stages in the cultivation of *Vitis vinife*ra are becoming accelerated. The overall effect of this acceleration and shift in growing season is a decrease in grape quality, as grapes experience an increase in sugar accumulation and decrease in acidity (Bezner Kerr et al. 2022). Moreover, higher air temperatures heat the grapes themselves, causing a loss of quality due to heat stress (Hannah et al. 2013). Air temperature also determines which grape varieties can thrive in a specific environment. For example, varieties such as Pinot Gris, Pinot Noir, and Chardonnay tend to ripen in lower temperatures of approximately 10-15.5 degrees Celsius, whereas Cabernet Sauvignon, Sangiovese, Grenache, and Zinfandel ripen at temperatures of approximately 15-21 degrees Celsius (Jones 2015). Wine grapes that ripen in higher temperatures are also higher in alcohol content (Jones 2015).

Wine grapes are also highly affected by the moisture regime and precipitation of the region. Low levels of precipitation over an extended period and droughts can increase water stress for grape vines, which ultimately decreases shoot growth and individual fruit size. Water stress also increases tannin and anthocyanin content of grapes (Bezner Kerr et al. 2022). In these cases, irrigation is then needed for successful viticulture. This presents another challenge, as freshwater resources across the globe are becoming depleted as climate change stresses continue.

Vineyard water usage increases as water is used to cool grapes that have warmed too much due to warmer air temperatures (Hannah, Roehrdanz et al. 2013). On the other hand, climate change is causing more frequent and intense flooding events that affect viticulture as well. Flooding can cause grape vine roots to experience signific hypoxic stress, which causes an increase in ethanol (alcohol content), acidity, and alanine (an amino acid), affecting grape quality (Ruperti et al. 2019).

As climate change continues to alter weather, temperature, and precipitation patterns, Mediterranean viticulture will become increasingly vulnerable, as it is located in a designated climate change hotspot. According to a recent study, between 25% and 73% of the current major wine-producing regions across the globe are predicted to become unsuitable for viticulture by 2050 when using the higher RCP 8.5 concentration pathway, and 19% to 62% of those regions will become unsuitable when using the lower RCP 4.5 (Hannah, Roehrdanz et al. 2013). Spain, France, and Italy are amongst the top countries by vineyard area and are also at the highest risk of becoming environmentally unsuitable for viticulture (OIV 2017). On the other hand, regions such as England that have never historically experienced the climate type needed for viticulture are now warming up to the required temperature and approaching climate conditions that are ideal for the cultivation of *Vitis vinifera*. Chinese viticulture has also been growing in quantity and popularity in the last three decades (Li 2017), and China is now one of the top wine-producing countries in terms of vineyard area (OIV 2017). Similarly, areas that experienced small yields of very high-quality grapes, such as Burgundy, Barolo, Champagne, are now experiencing more frequent high-quality yields due to more frequently ideal climate conditions.

Soil Constraints on Viticulture

Like climate, soil plays an extremely important role in the cultivation of wine grapes. Terroir can be greatly affected by changes in soil, thereby affecting grapes and wine-production. Soil temperature, soil water content, and soil mineral supply are the most important factors for viticulture (van Leeuwen, Roby et al. 2018). Each of these soil elements affects a specific aspect of viticulture.

Soil temperature most substantially affects grapevine development or “phenology”, similar to how air temperature affects vine development. If the soil temperature is too warm, grapes will become ripe too quickly, resulting in grapes high in sugar and low in acid (van Leeuwen, Roby et al. 2018). On the other hand, if grapes ripen too late in the season due to cold soils, they may not reach desired ripeness which results in less flavorful wine with an excess of “green flavors,” or green vegetable notes. Soil temperature depends on soil color albedo (the amount of UV reflection), slope steepness, and slope direction. Although warmer soil temperatures often produce negative impacts on grapes, some *Vitis vinifera* varieties thrive on warmer soils, so this is important to consider as well.

Soil water content is highly influenced by climatic patterns, such as precipitation and evapotranspiration. Soil porosity and texture are characteristics of soil that determine the soil’s ability to store water, an important aspect of viticulture. On vineyards across the globe, soil water holding capacity is highly variable allowing for different viticultural methods and produced grapes (van Leeuwen, Roby et al. 2018). Soils with low water content often limit grape growth and acid content. However, in certain cases limited soil water supply can be beneficial for grapes, as it increases skin phenolics, creates high-quality aromas, and improves wine aging (van Leeuwen, Roby et al. 2018).

Lastly, soil mineral supply plays a large role in grape cultivation, especially soil nitrogen content. Nitrogen affects vine vigor, size of grape yield, individual grape size, sugar content, acidity, and aromas (van Leeuwen, Roby et al. 2018). However, many processes must occur within soil and the soil must have specific characteristics in order for nitrogen in its organic form to be converted to its viticulturally usable NO3- form. In most grape varieties, moderately high nitrogen content is desired, but excessively high nitrogen content is not desired (van Leeuwen, Roby et al. 2018). This is because overly abundant nitrogen levels make grapes more susceptible to rot. In either case, it is necessary to note that red and white wine grape varieties require different ideal nitrogen levels, making soils a critical component of viticulture. Soils can supply other major minerals such as phosphorus, potassium, magnesium, and calcium, but they are not nearly as critical to viticulture as nitrogen (van Leeuwen, Roby et al. 2018).

Methods

For this study, research was focused on the geographical region of southern France. This region contains three prominent wine growing regions, including Languedoc-Roussillon, Provence, and the Rhone Valley. Twelve data sets were collected and manipulated in order to carry out the geographic information system (GIS) approach to display how climate change will impact Mediterranean viticulture in the future.

Data Collection

To display the effects of climate change on viticulture, both raster and vector data for land cover (vineyards), soil type, and climate variables were collected from European databases. From the Copernicus Land Monitoring Service, vector and raster files of European land cover were obtained, from which vineyards could be isolated and displayed. From the European Soil Database, vector and attribute data were downloaded, as well as a legend file displaying the soil classification according to the World Reference base for Soil Resources. Lastly, the following four climate variables were studied in this project: mean annual temperature, total annual precipitation, mean length of dry spells, and mean volumetric soil water (VSW) content in layer 1 soils. Raster datasets including spatial information on these four variables were downloaded from the Copernicus Climate Change Service. All four datasets contained information based on two French models (IPSL-CM5A-LR and IPSL-CM5B-LR) and the RCP 4.5 experiment. Additionally, the four individual datasets contained downscaled bioclimatic projections for Europe between the years 1950 to 2100. Therefore, it was necessary to extract the 2020 data as well as the 2050 data from each dataset in order to observe the change in each variable over 30 years, in the future. Please refer to the Appendix (Detailed Steps in the Making of Figures 3-10) to see exactly what data was downloaded from Copernicus in regards to these four climate variables.

GIS Mapping

After all data was collected, ArcGIS Pro was utilized to create a series of maps to compare the climatic conditions that southern French vineyards experienced in 2020 and the conditions they are predicted to experience in 2050. Figure 1, which is located in the Background section, simply displays the region in which this study takes place, southern France. In this figure, the southern French vineyards are shown, including all those in the Languedoc-Roussillon, Provence, and Rhone Valley regions. This figure displays the vineyard land cover vector data from the Copernicus Land Monitoring Service, which provides a reference for the following figures showing soil type coverage and climatic conditions on vineyards in this region. Please refer to the Appendix (Figure 1) for detailed methods and steps utilized in the making of this figure. Figure 2, which is also located in the Background section, displays the soil types present in the region of interest, southern France. The same spatial extent is used in this figure as in Figure 1. Similarly, Figure 2 also provides a reference for interpreting the ways in which climate change will affect viticulture, as soils play an essential role in grape cultivation. Please refer to the Appendix (Figure 2) for detailed methods and steps utilized in the making of this figure.

Figures 3-10 present the climatic conditions in the south of France. In Figures 3 and 4, the average annual temperature (Celsius) in the region is shown for 2020 and 2050, respectively. In Figures 5 and 6, the total annual precipitation (mm/year) in the region is shown for 2020 and 2050 respectively. In Figures 7 and 8, the average length of dry spells (days) in the region is shown for 2020 and 2050 respectively. In Figures 9 and 10, the average volumetric soil water (VSW) content in layer 1 soils (m^3 m^-3) in the region is shown for 2020 and 2050, respectively. Please refer to the Appendix (Figures 3-10) for detailed steps in the making of these map layouts.

Data Analysis

Analysis of the data was conducted in both ArcGIS Pro and JMP. After constructing Figures 3-10, a vineyard land cover raster (also obtained from Copernicus Land Monitoring Service) was added to each figure. Please refer to the Appendix (Southern French Vineyards Raster Layer to be used in Figures 3-10) for the detailed steps in the construction of this raster layer. Using spatial analyst tools in ArcGIS pro, this raster layer was multiplied by each of the eight climate variable rasters (2020 and 2050 projections). Eight new raster layers were then created, containing pixel values representing the climatic conditions on all vineyard areas in the region of interest, for both 2020 and 2050 projections. Following this, eight tables, containing the pixel values for each new multiplied raster, were constructed and were each individually exported as a text file. These eight text files were then imported into excel, where they were re-labeled and joined. Please refer to the Appendix (Figures 3-10) for detailed steps carried out in the raster calculation, table creation, and text file exportation process.

To show the difference in the four climate variables on vineyards between 2020 and 2050, four new map layouts were created (Figure 11 a-d). Please refer to the Appendix for detailed steps in the construction of these rasters and map layouts.

After the data was organized in Excel, it was imported into JMP. Histograms were constructed to show the difference in climate variables on vineyards between 2020 and 2050 (such as the distribution average annual temperatures on vineyards in 2020 vs. the projected distribution of average annual temperatures on vineyards in 2050). Four sets of histograms were constructed to display the changes in each climate variable. Scatter plots were also constructed to show correlation between projected climatic conditions on vineyards for 2050 based on location.

Results

The results of this study show that there will be a definitive change in the climate in the south of France between 2020 and 2050. According to downscaled climate projections based on the RCP 4.5 experiment, there will be an increase in average annual temperature (see Figures 3 and 4), a decrease in total annual precipitation (see Figures 5 and 6), an increase in average length of dry spells (see Figures 7 and 8), and a very slight increase in average volumetric soil water (VSW) content in layer 1 soils (see Figures 9 and 10).

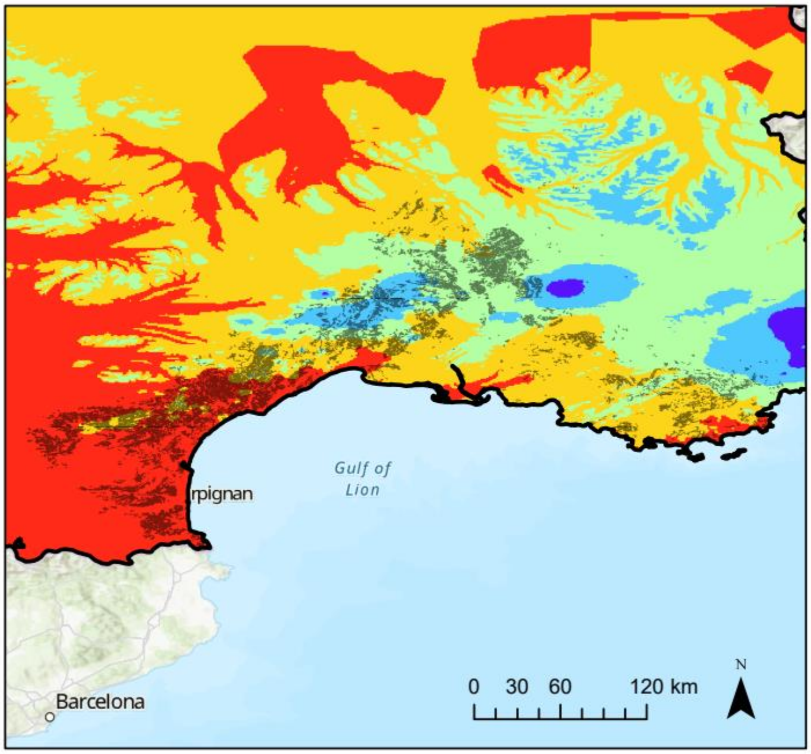


Figure 3.) 2020 Mean Annual Temperature in the South of France, with a Focus on Vineyards

Figure 3. Shows the mean annual temperatures in the south of France in 2020, sourced from downscaled climate projections using the model IPSL-CM5A-LR and experiment RCP 4.5. Vineyards in the Languedoc-Roussillon, Provence, and Rhone Valley regions are also displayed for reference.

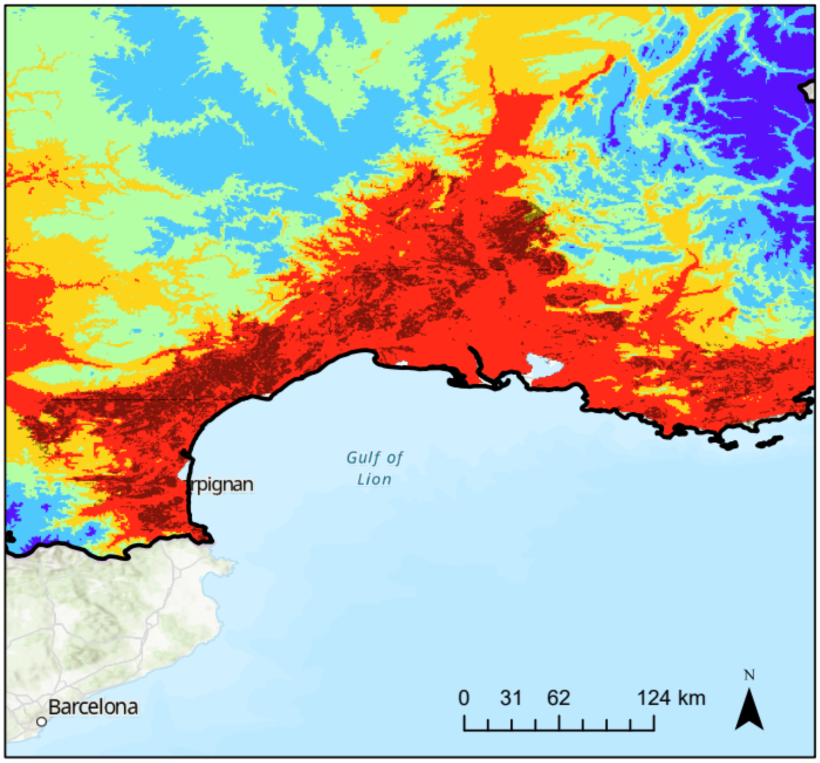


Figure 4.) Projected Mean Annual Temperature in the South of France in 2050, with a Focus on Vineyards

Figure 4. Shows the mean annual temperatures in the south of France in 2050, sourced from downscaled climate projections using the model IPSL-CM5A-LR and experiment RCP 4.5. Vineyards in the Languedoc-Roussillon, Provence, and Rhone Valley regions are also displayed for reference.

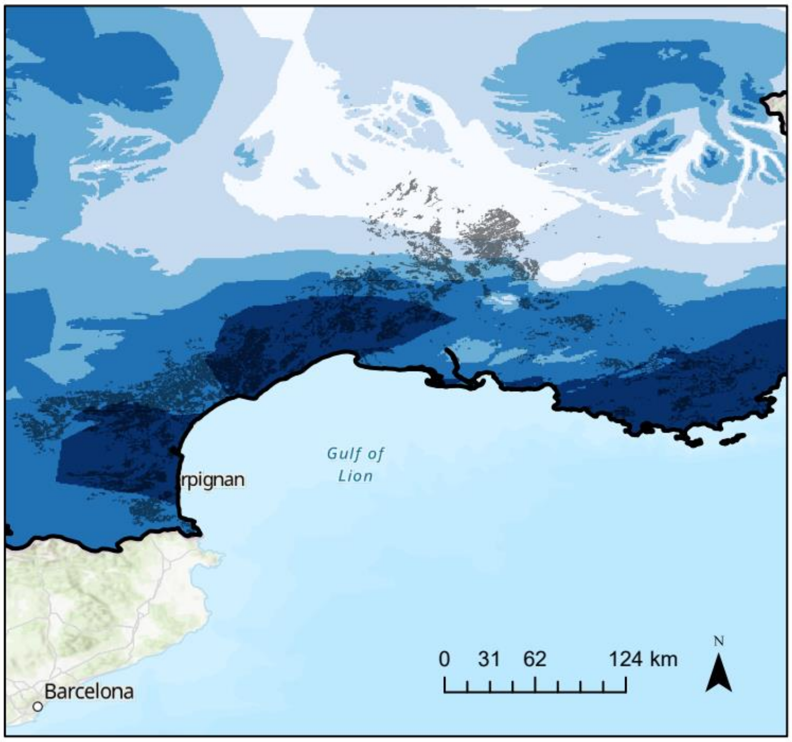


Figure 5.) 2020 Annual Precipitation in the South of France, with a Focus on Vineyards

Vineyards

▨ Area

Annual Precipitation (mm/year)

- ≤1046
- ≤1189
- ≤1347
- ≤1640
- ≤2384

Figure 5. Shows the annual precipitation in the south of France in 2020, according to downscaled climate projections using model ISPL-CM5A-LR and experiment RCP 4.5. Vineyards in the Languedoc-Roussillon, Provence, and Rhone Valley regions are also shown for reference.

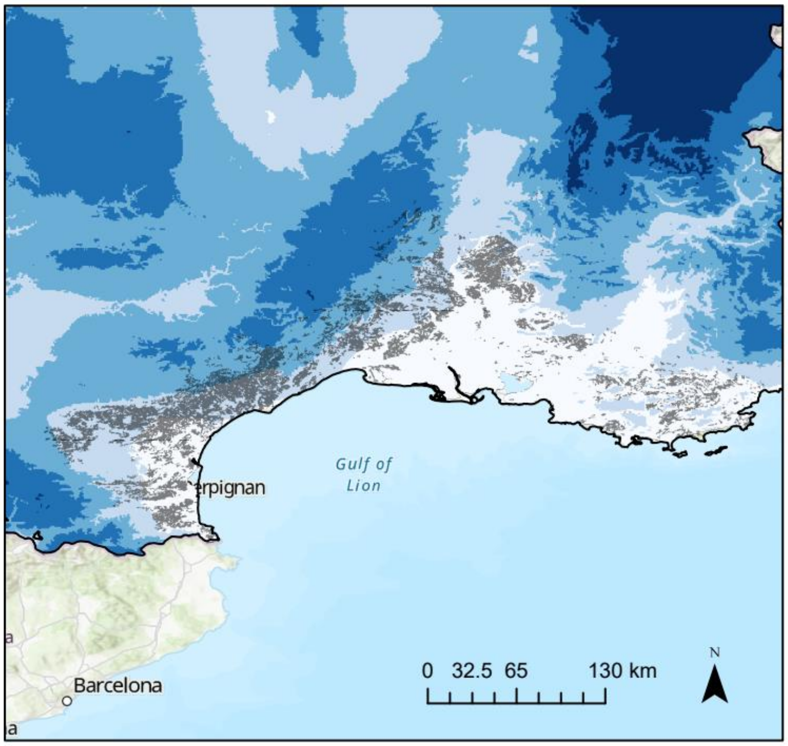


Figure 6.) Projected Annual Precipitation in the South of France in 2050, with a Focus on Vineyards

Vineyards

▨ Area

Annual Precipitation (mm/year)

- ≤811
- ≤978
- ≤1183
- ≤1472
- ≤2139

Figure 5. Shows the annual precipitation in the south of France in 2020, according to downscaled climate projections using model ISPL-CM5A-LR and experiment RCP 4.5. Vineyards in the Languedoc-Roussillon, Provence, and Rhone Valley regions are also shown for reference.

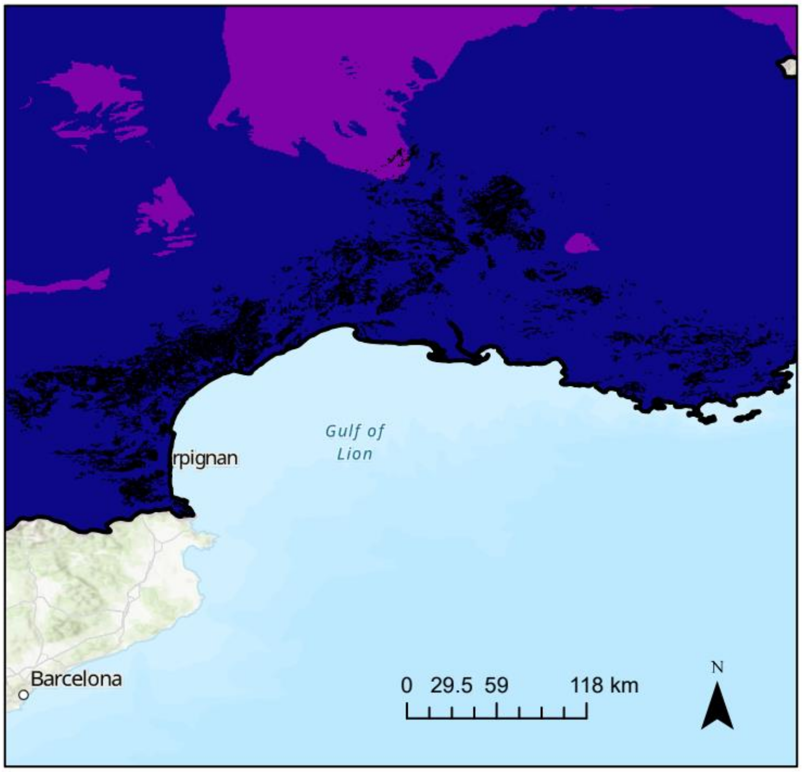


Figure 7.) 2020 Mean Length of Dry Spells in Southern France, with a focus on Vineyards

Vineyards

■ Vineyard Area

Mean Length of Dry Spells (Days)

- ■ ≤8.3
- ■ ≤9.1
- ■ ≤9.6
- ■ ≤10.7
- ■ ≤14.1

Figure 7. This map displays the mean lengths of dry spells in the south of France in 2020 according to downscaled climate projections using the model IPSL-CM5B-LR and experiment RCP 4.5. Vineyard areas in the Languedoc Roussillon, Provence, and Rhone Valley regions are also shown for reference.

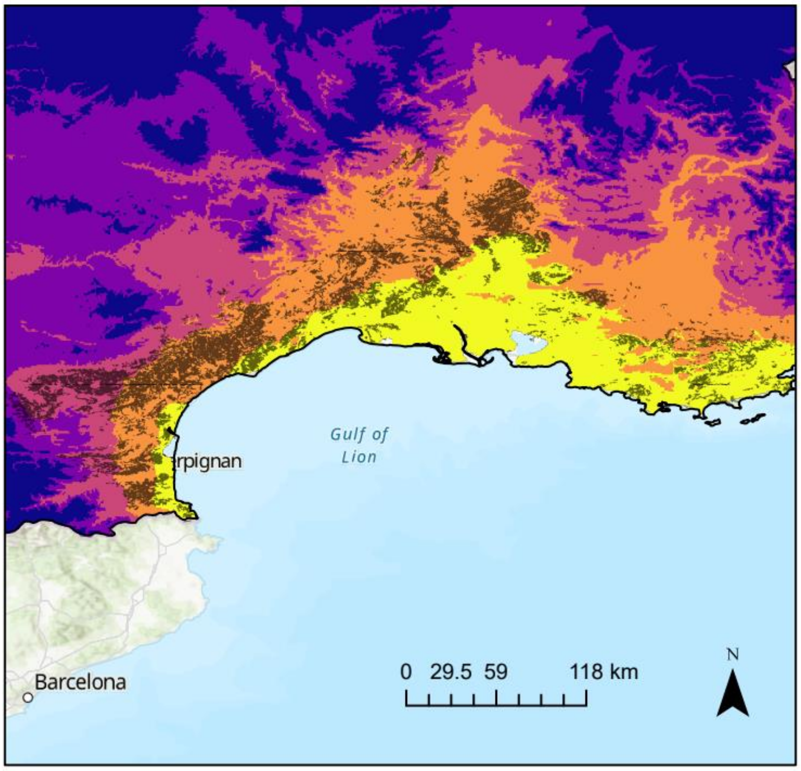


Figure 8.) Projected Mean Length of Dry Spells in Southern France in 2050, with a Focus on Vineyards

Vineyards

■ Vineyard Area

Mean Length of Dry Spells (Days)

- ■ ≤9.7
- ■ ≤10.5
- ■ ≤11.8
- ■ ≤13.6
- ■ ≤17.9

Figure 8 . This map displays the projected mean lengths of dry spells in the south of France in 2050 according to downscaled climate projections using model IPSL-CM5B-LR and experiment RCP 4.5. Vineyard areas in the Languedoc Roussillon, Provence, and Rhone Valley regions are also shown for reference.

Figure 9.) 2020 Volumetric Soil Water in Layer 1 in the South of France, with a Focus on Vineyards

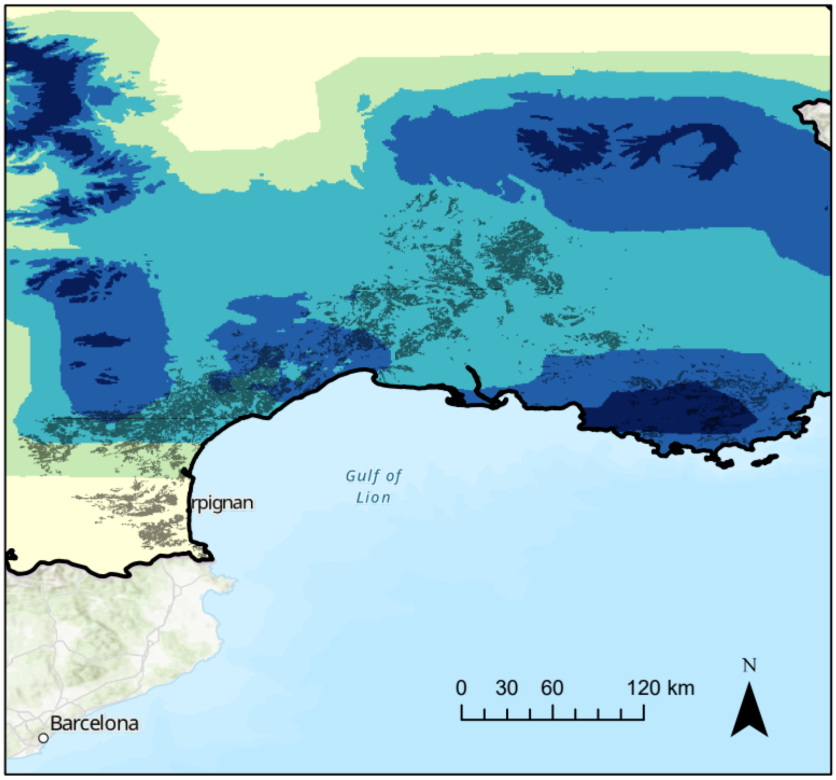


Figure 9. Shows the volumetric soil water content in layer 1 soils in the south of France in 2020, according to downscaled climate projections using model IPSL-CM5A-LR and experiment RCP 4.5. Vineyard areas in the Languedoc-Roussillon, Provence, and Rhone Valley regions are also shown for reference.

Figure 10.) Projected Volumetric Soil Water in Layer 1 in the South of France in 2050, with a Focus on Vineyards

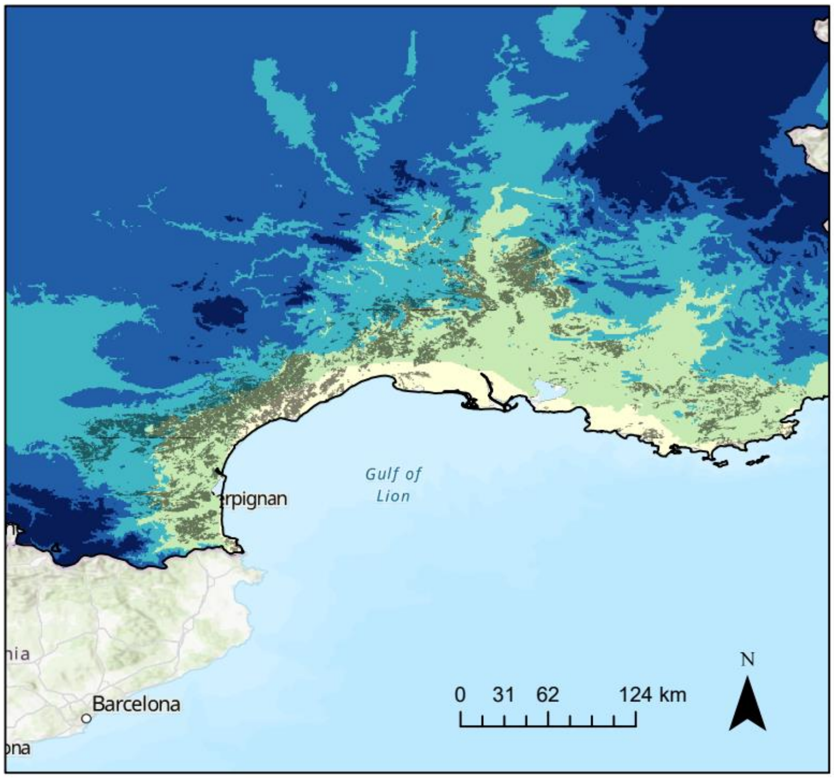


Figure 10. Shows the projected volumetric soil water content in layer 1 soils in the south of France in 2050, according to downscaled climate projections using model IPSL-CM5A-LR and experiment RCP 4.5. Vineyard areas in the Languedoc-Roussillon, Provence, and Rhone Valley regions are also shown for reference.

More specifically, these shifts are reflected in the vineyard areas in the southern France region, which make up the Languedoc-Roussillon, Provence and Rhone Valley wine regions. Figures 11 (a) through 11 (d) illustrate the amount of change in each of these climate variables on the vineyard areas. In terms of average annual temperature, vineyards are projected to experience between 5.25 and 18.84 degrees Celsius of warming by 2050 (Figure 11a). Annual total precipitation is projected to decrease by as much as 1648.87 mm/year in some areas but increase by 313.43 mm/year in other areas (Figure 11b). The average length of dry spells on vineyard areas is projected to increase by at least 1.6 days in some vineyard areas, and at most 8.85 days in other vineyard areas (Figure 11c). Lastly, VSW will remain relatively constant, although there will be areas of slight increase and slight decrease, as shown in Figure 11 (d).

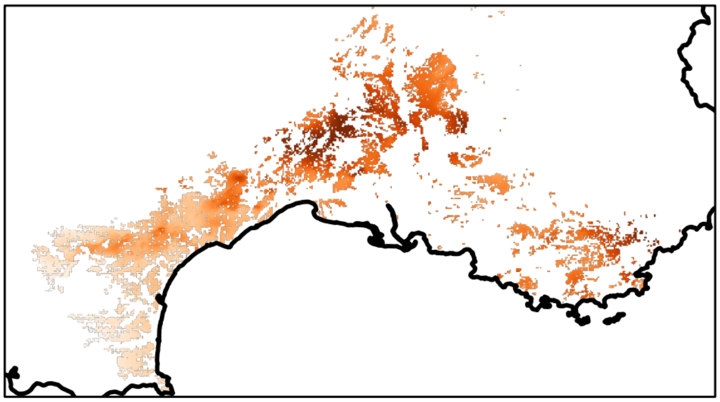


Figure 11 (a)

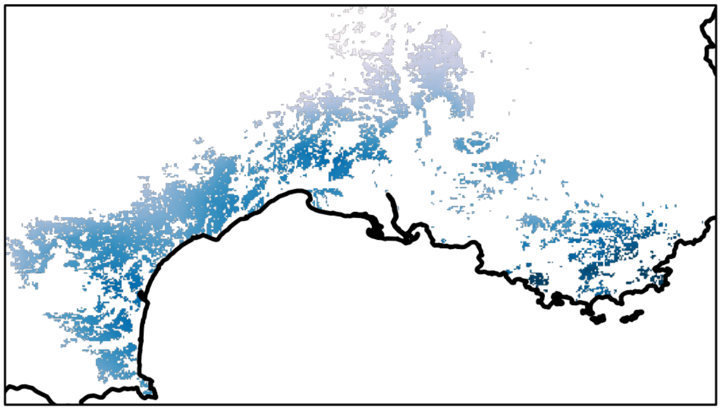


Figure 11 (b)

*Note that Figure 11 (b) displays a decrease in precipitation between 2020 and 2050. The 2020 raster layer was subtracted from the 2050 data (see Appendix for more details)

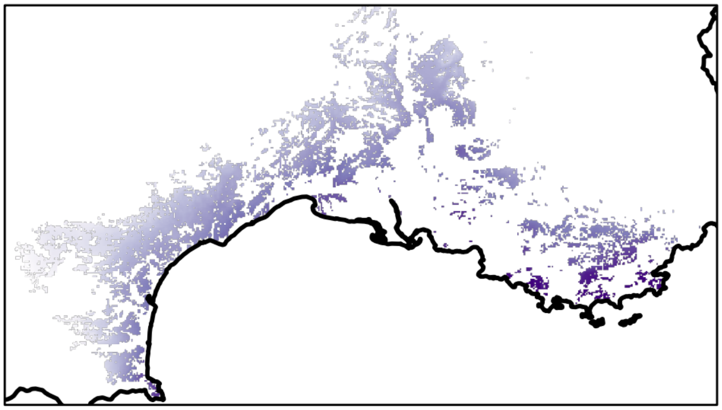


Figure 11 (c)

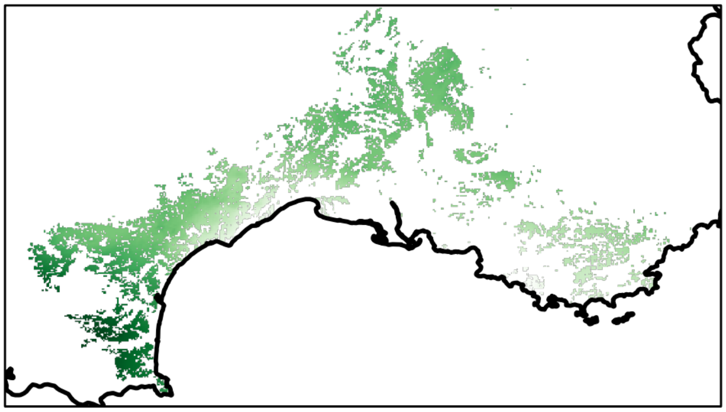
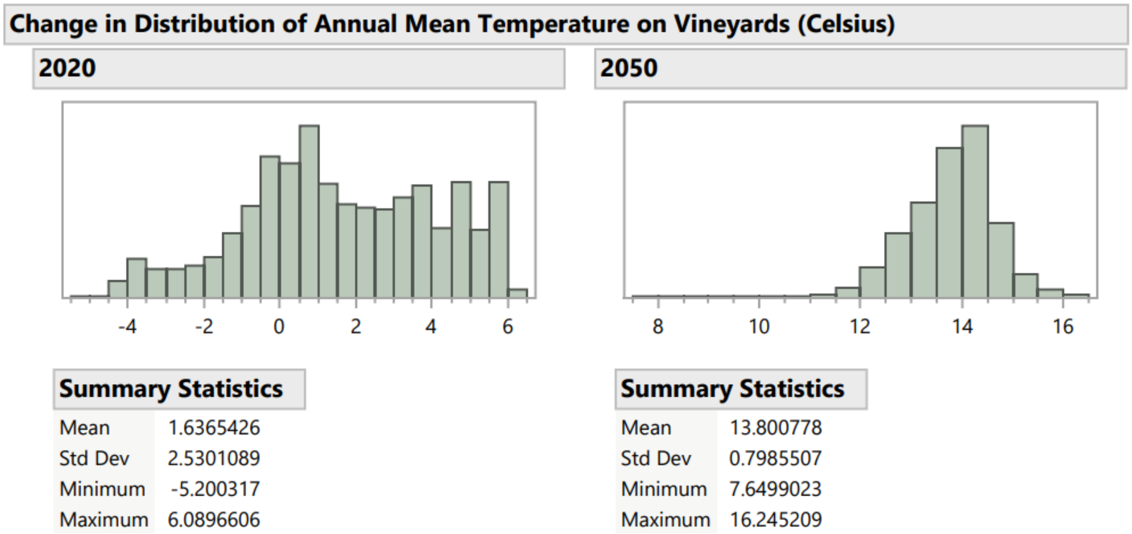


Figure 11 (d)

Figures 12 through 15 show the change in distribution of these four climatic variables on vineyard areas between 2020 and 2050, based on the RCP 4.5 experiment projections. These histograms and summary statistics provide necessary information including the change in mean, minimum and maximum values of each variable on vineyards, which are not shown in Figures 3-11. The mean average annual temperature on vineyards will increase from 1.63 degrees Celsius in 2020 to 13.80 degrees Celsius in 2050. Both minimum and maximum temperatures will also increase (Figure 12 a & b). The mean total annual precipitation on vineyards will decrease from 1575.13 mm/year to 848.42 mm/year. Both minimum and maximum temperatures will also decrease (Figure 13 a & b). There will be an increase in the average length of dry spells on vineyards, from an average of 7.83 days to 12.94 days. Both minimum and maximum lengths of dry spells will also increase (Figure 13 a & b). Lastly, the VSW content in layer 1 soils on vineyards is predicted to remain relatively constant, with only a marginal increase in average VSW from 0.24 to 0.25 m^3m^-3. The 2050 minimum VSW content will increase very slightly, but the maximum VSW content will decrease slightly.

Figure 12

(a) (b)



Summary Statistics (2020)

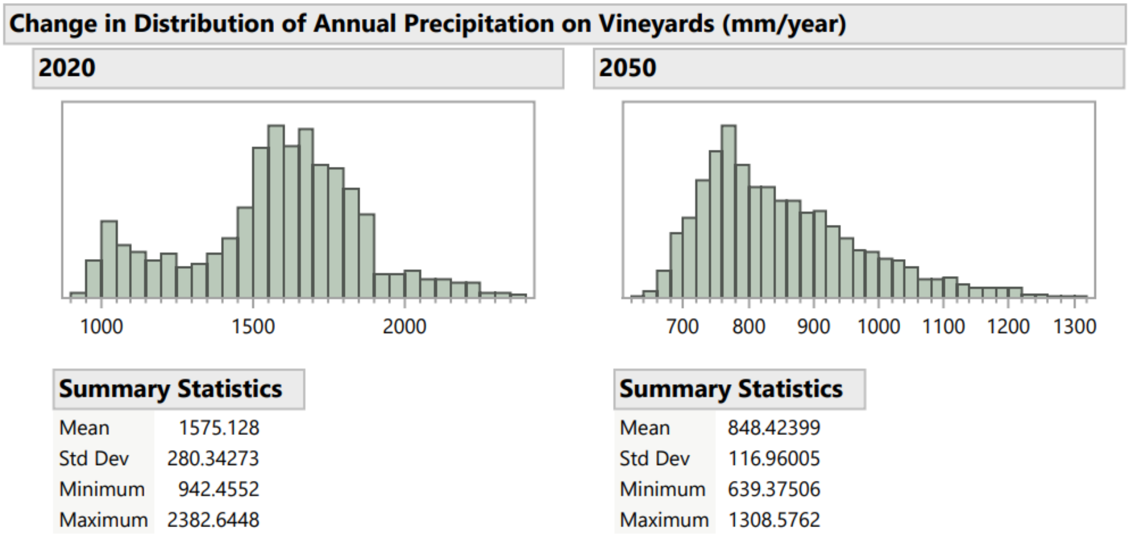
Mean	1.6365426
Std Dev	2.5301089
Minimum	-5.200317
Maximum	6.0896606

Summary Statistics (2050)

Mean	13.800778
Std Dev	0.7985507
Minimum	7.6499023
Maximum	16.245209

Figure 13

(a) (b)



Summary Statistics (2020)

Mean	1575.128
Std Dev	280.34273
Minimum	942.4552
Maximum	2382.6448

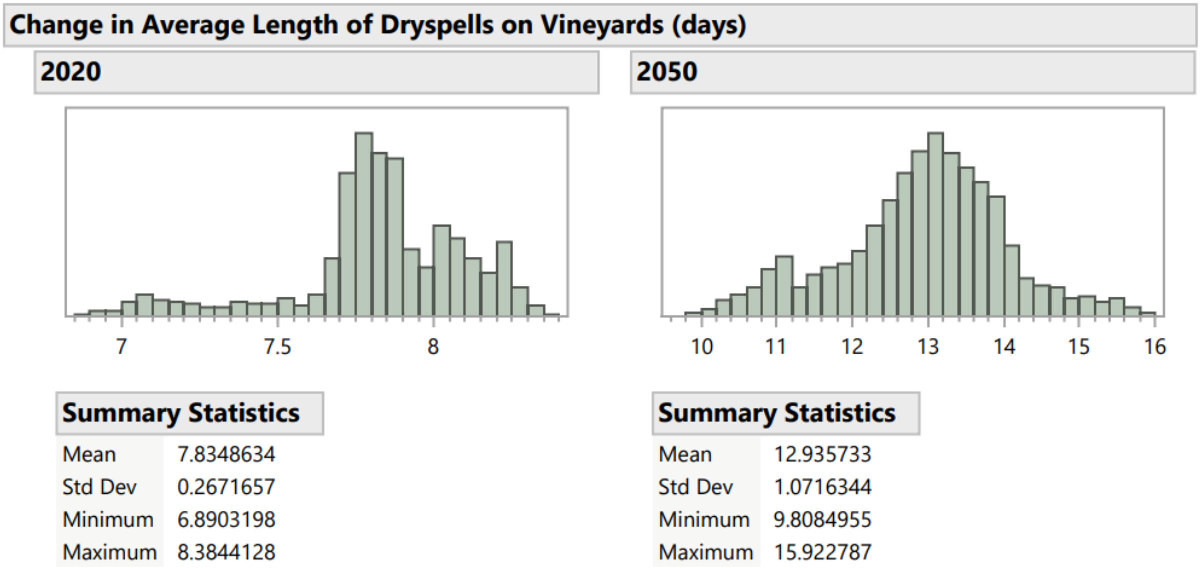
Summary Statistics (2050)

Mean	848.42399
Std Dev	116.96005
Minimum	639.37506
Maximum	1308.5762

Figure 14

(a)

(b)



Summary Statistics (2020)

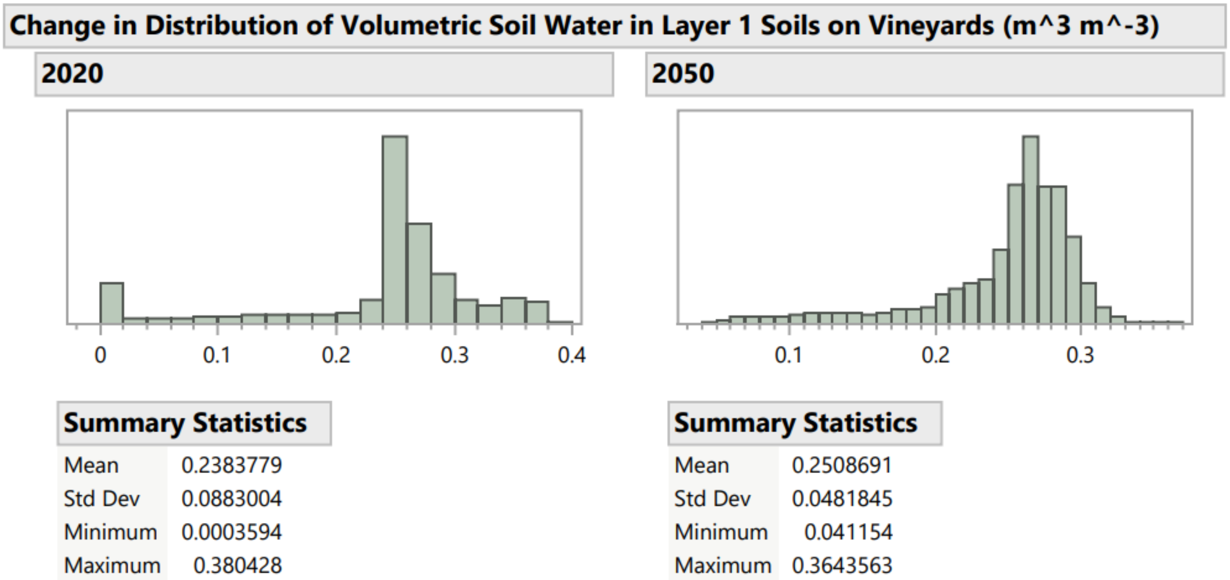
Summary Statistics	
Mean	7.8348634
Std Dev	0.2671657
Minimum	6.8903198
Maximum	8.3844128

Summary Statistics	
Mean	12.935733
Std Dev	1.0716344
Minimum	9.8084955
Maximum	15.922787

Figure 15

(a)

(b)



Summary Statistics	
Mean	0.2383779
Std Dev	0.0883004
Minimum	0.0003594
Maximum	0.380428

Summary Statistics	
Mean	0.2508691
Std Dev	0.0481845
Minimum	0.041154
Maximum	0.3643563

Figures 16 and 17 show correlation between climate variables based on their location. In 2050, it is predicted that vineyard areas experiencing lower average annual temperatures will also receive more precipitation throughout the year. Conversely, vineyards with higher average annual temperature will receive less precipitation (Figure 16). Tying in the other two climate variables, dry spells and VSW content, Figure 16 shows how vineyards that will experience longer dry spells in 2050 will also have lower VSW content in their layer 1 soils. Moreover, these areas are likely to have higher average annual temperatures, anywhere between 14 and 16 degrees Celsius.

Figure 16

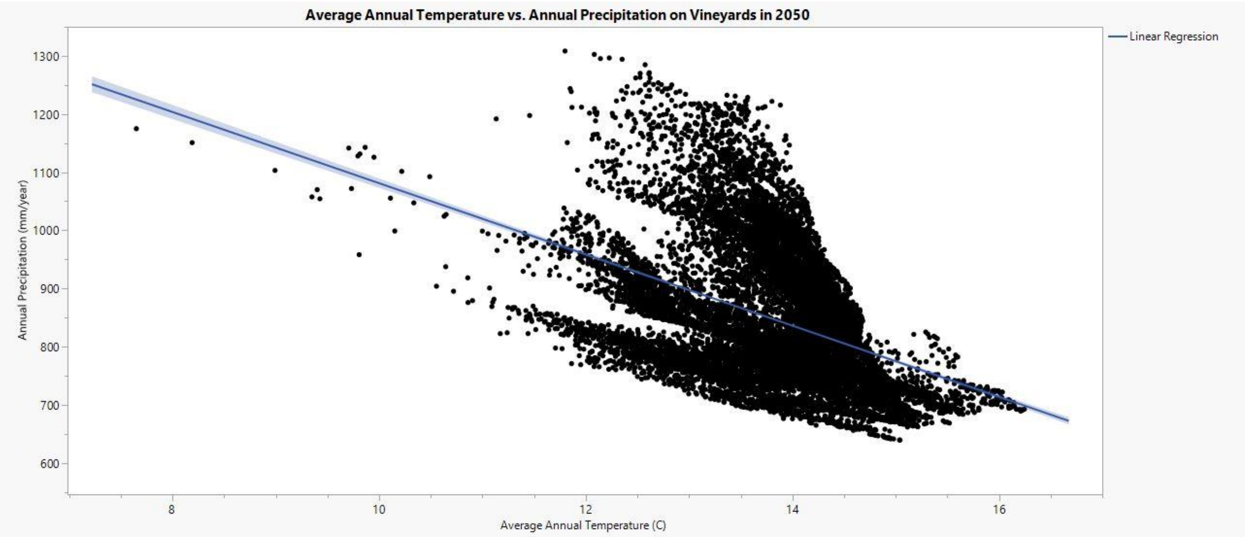


Figure 16. Projected average annual temperatures on vineyards in 2050 compared to projected annual precipitation on vineyards in 2050 with a generated linear regression line to show correlation between variables.

Figure 17

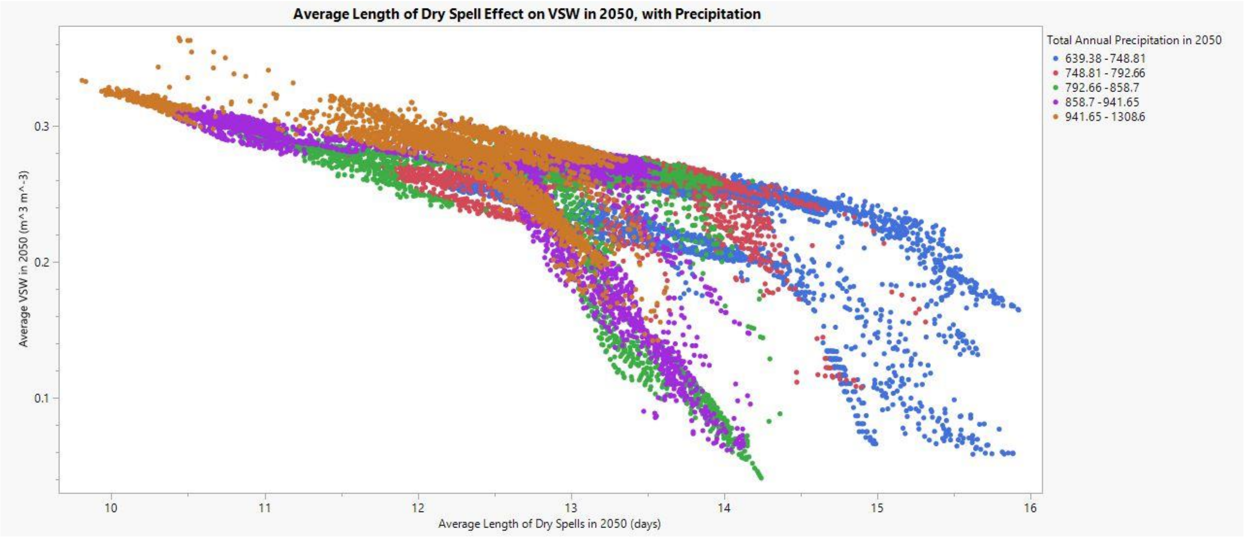


Figure 17. Projected average length of dry spells on southern French vineyards in 2050 compared to the projected average VSW on southern French vineyards in 2050, with projected total annual precipitation on vineyards in 2050 overlaid and color coded.

Discussion

Implications of 2050 Climate Change Projections for Southern French Grapes

The results of this study clearly show that the area of interest, southern French vineyards, will experience significant shifts in climate variables by the year 2050 according to downscaled climate projections based on two French models and the RCP 4.5 experiment. Although these projections show just one possible scenario of future climate change out of thousands, because they are based on only two specific French models and only one RCP experiment, it is important to understand how viticulture could potentially be affected. The shifts shown in the results will have considerable impacts on viticulture, as grapes are a cultivated species known to be highly sensitive to shifts in climate, along with topography and soils (Deloire 2008). Since France is one of the largest wine producing countries in the world in terms of vineyard area and volume of wine, as well as the world's top producer in value, it is necessary to understand how both grape quality and grape yields will be at stake in the coming decades (Alonso Ugaglia et al. 2019). In this study, vineyards in Languedoc-Roussillon, Provence, and the Rhone Valley were evaluated, which are the three most southern wine-producing regions in France. The geographical location of these vineyards situates them within the Mediterranean climate and chaparral biome, making them unique from all other French wine regions, which experience a temperate climate. Therefore, grapes cultivated in the south are extra susceptible to the effects of climate change, as the Mediterranean Basin is considered by the IPCC to be a climate change hotspot. The most widely grown varieties of *Vitis vinifera* in these southern French wine regions include Syrah, Grenache, Mourvèdre and Carignan (Fraga et al. 2012). Though these grapes thrive in the south of France, and warmer climates in general, the results of this study show that these grapes' resiliency to warm climates may be put to the test by 2050, according to RCP 4.5 projections.

i. Temperature

The most “unambiguous” consequence of climate change on viticulture is the projected rise in temperature affecting vine and grape growth stages (Venios et al. 2020). Syrah, Grenache, Mourvèdre, Carignan and other grape varieties cultivated in the south of France are known for their famously bold fruity flavors, low acidity, and robust tannins (SevenFifty). These characteristics form as a result of these varieties’ unique grapevine phenology. Phenology refers to the growth and development stages of a plant throughout a growing season, which is closely related to climatic factors (Giese et al. 2020). Grape growers use the Eichhorn-Lorenz (E-L) system to describe the stages, which include the following, as well as many more specific stages in between: dormancy and winter bud, budburst, flowering, fruit set, veraison, harvest, and the beginning of leaf fall (Giese et al. 2020). The most critical stage is veraison, or the beginning of the grape ripening process. The southern French grape varieties and other warm climate varieties tend to reach veraison later in the season. Once grapes start ripening, they develop their prized flavors and characteristics. Temperature has the largest effect on grapevine phenology, as the stages can be hastened or slowed due to temperatures that are too high or too low. Studies show that ideal grapevine development requires temperatures that range between approximately 18° Celsius in the hottest months of the growing season and about -1° Celsius in the coldest months of the growing season (Jones 2015).

However, climate projections for 2050 indicate that the average annual temperature on southern French vineyards may increase by up to 18.84° Celsius in certain areas (see Figure 11a). Although this result seems extraordinarily high, which may be an issue with the original dataset and projections, this more than noticeable temperature difference is projected to occur on the northernmost vineyards (Figure 11a). These vineyards are located in two mountainous areas, the Parc national des Cevennes and the Parc naturel régional des Baronnies provençales, which encompasses the foothills of the French Alps. In 2020, the average annual temperatures in these areas ranged between -2.2 and 4 degrees Celsius (Figure 3) but are projected to warm to somewhere between 12.1 and 17 degrees Celsius (Figure 4). Because these areas were colder than the rest of the region in 2020, yet will experience the same warming trends, they will have the largest increase in temperature, and thereby the largest effect on grapevine phenology.

Phenological development of grapevines will be accelerated because temperature is correlated with plant metabolic processes (Geise 2020). Therefore, grapes will reach veraison too quickly and ripening will occur too soon in the growing season. This will cause grapes to overripen on the vines, allowing for more sugars to develop and acidity to lower. Both consequences will lower the overall quality of the grapes for wine production. If temperatures are consistently too hot, the grapes may even become abscised from the vine prior to harvest, falling to the ground, rendering them completely unusable for wine production (Jones 2015). The northern vineyards located in mountainous regions that will experience the largest changes in temperature will be at the highest risk of yielding grapes that are of low flavor quality.

Across all southern French vineyards, the lowest average annual temperature is projected to be 7.65° Celsius, which would likely allow grapevines to develop at the proper rate in 2050 (Figure 12b), with minimal changes in grapevine phenology. However, the highest average annual temperature across these vineyards is projected to be around 16.25° Celsius (Figure 12b). Although we do not know which vineyards will experience these highest temperatures, it is important to note that their average *annual* temperature is almost as high as the desired *maximum* temperature, 18° C, which will result in major changes to grapevine phenology and the previously described effects on grapes.

Studies have shown that Syrah grapes are particularly sensitive to temperature, as those grown in cooler climates with high differences in day and nighttime temperatures are peppery in aroma, whereas those grown in warmer climates with smaller differences in day and nighttime temperatures are less peppery and much fruitier in flavor (Jones 2015). As Figure 11(a) and Figure 12 show, the projected increase in average temperature will likely cause warm-climate Syrah grapes in the south of France to develop at an accelerated rate, causing their fruitiness to be overcome by an excess amount of sugar which is not desired by winemakers. Syrah grapes grown in the northern mountainous Rhone Valley regions will be at the highest risk in 2050.

Although flavor is the most important quality of wine grapes, ideal grape color is also valued in wine production. Grapes that are very rich in color are most desired by winemakers. Grape color development during cultivation is also dependent on temperature during the growing season, as hotter temperatures inhibit anthocyanin biosynthesis, the main driver of grape color (Venios et al. 2020). Therefore, it is likely that grapes in southern France in 2050 will experience a reduction in color, especially those in the eastern Languedoc and Rhone Valley regions, rendering them less ideal for high quality wine production.

ii. Precipitation and Dry Spells

While temperature highly affects the flavor of grape varieties, patterns of annual precipitation and droughts can affect the *quantity* of grapes yielded in addition to their quality. Viticulture requires both dry periods and wetter periods depending on the stage of vine development. Limited precipitation and long droughts can cause water stress, impairing grapevine photosynthesis and reducing “vine vigor,” which is the rate of shoot growth (Geise 2020). This is extremely detrimental during the flowering to ripening period of grapevine development, as the plant is not able to take up enough water to support lots of growing grapes.

Another possibility is that the individual grapes developed are smaller in size, due to lack of sufficient water resources. However, water stress affects grapes less significantly during later grapevine growth stages leading up to harvest, in which dryer conditions are actually favorable (Fraga et al. 2012). Therefore, it is likely that southern French vineyards will experience smaller grape yields in 2050 than they did in 2020, as they will experience water stress due to a notable decrease in total annual precipitation and increase in dry spell length (Figures 11b, 11c, 13 and 14). Although the data does not provide information regarding the specific point during the growing season at which the longest droughts will occur, it still indicates that the risk of water stress in grapevines is likely on these vineyards in 2050. Since the average length of dry spells in 2050 may be up to 8.85 days longer than those in 2020, it is possible that grapevines will experience detrimental effects on grape yield if those droughts were to occur during early development stages.

It is also important to note that the vineyards that are projected to experience the highest temperatures in 2050 will also receive the least total annual precipitation in 2050 (Figure 16). Vineyards in these areas will suffer disproportionately, as both loss of high-quality flavor and smaller quantities of grapes yielded will greatly affect their ability to produce high quality wine.

iii. Soil Volumetric Water Content

The final climate variable that was analyzed in this study is volumetric soil water content of layer 1 soils. Figure 17 shows that the total amount of annual precipitation and average length of droughts on vineyards has a strong impact on the volumetric soil water content of vineyard soils. Vineyards experiencing the longest droughts on average and receiving the least precipitation are also those with the lowest volumetric soil water content. However, Figure 15 shows that volumetric soil water content of southern French vineyard soils are not projected to change dramatically by 2050 despite the projected decrease in annual precipitation and increase in the length of dry spells. The average VSW across all vineyard areas only increases by 0.01 m^3m^{-3} between 2020 and 2050 (Figure 15).

But even more perplexing is the projected *increase* of VSW on some southern French vineyards by 2050, as shown by Figure 11(d). The southernmost vineyards in the Languedoc-Roussillon region, just north of the Spanish border, are predicted to experience soils with higher VSW content in 2050 than they had in 2020 (Figure 11d). The maximum increase may be up to 0.33 m^3m^{-3} more in 2050 than in 2020 (Figure 11d). This result requires attention, as it does not fit logically with the predicted decrease in total precipitation (Figure 13) and increase in average dry spell length (Figure 14) on those same vineyards.

A possible explanation for this trend may be sea level rise, as the vineyard areas that are predicted to experience an increase in VSW are located on the southernmost coastal areas of France (see Figures 10 and 11d). According to the IPCC, sea level rise in coastal zones causes an increase in flooding, ground and surface water, and impeded drainage (Oppenheimer et a. 2019). Increase in VSW content would be a consequence of this trend. Therefore, it is necessary to understand how increased VSW, potentially caused by sea level rise, will affect viticulture in this area. If sea level rise is indeed the reason that soils in this area of the studied region have higher VSW content, it can be inferred that they will also have higher levels of salinity, rendering them less suitable for viticulture (van Leeuwen et al. 2018).

Though water stress has a negative effect on grape cultivation, high-moisture soils can also present challenges for grape cultivation. Viticulture requires the Goldilocks standard when it comes to moisture—just the right amount. The grape varieties in the south of France typically thrive under moderate water deficit and no irrigation. The increase in VSW content on some vineyards indicates possible negative impacts on grapevines (Figure 11d). Soils with high VSW content are also more likely to become oversaturated due to extreme precipitation events, which will become more frequent and severe in coming years due to climate change (Ali et al. 2022, Oppenheimer et al. 2019). A result of soil oversaturation on grapevines is hypoxia, or oxygen deprivation, in the root zone (Ruperti et al. 2019). Grapevines are then forced to respond to and later recover from hypoxia, resulting in an increase in ethanol (alcohol) and three different types of acid—GABA, succinic acid, and alanine (Ruperti et al. 2019). Increased alcohol content and acids in grapes is not ideal for winemaking. Moreover, root growth and lateral expansion is constrained, preventing grapevines from establishing large, strong root networks (Ruperti et al. 2019). This could result in grapevines that are highly susceptible to damage from extreme weather. The vineyards that will experience the most substantial increase in VSW, and as a result, high alcohol and acidity grape yields, are located in the Languedoc-Roussillon region, just north of Spain (Figure 11d).

VSW content also plays a role in the development of grape skin phenolic compounds, which influence grape aromas (Koundouras 2018). Grapevines growing in soils with moderate water stress can produce grapes with better aromas than those growing in wetter soils. Therefore, it can be assumed that grapes on vineyards near Spain, with higher VSW content, may have lower quality aromas. Conversely, aromas may remain desirable in some southern French grapes in 2050. These would include those growing on other southern French vineyards that are projected to experience moderate to high water stress due to lack of precipitation and increased drought length, which was discussed in the previous section. These areas will also experience a decrease in VSW content. Figures 11 (b), 11 (c), and 11 (d) show that vineyards in the Provence region (vineyards furthest east) will experience this trend.

Effects of Projected Climate Change on Southern French Soils & Indirect Effects on Viticulture

In addition to climate change’s direct effects on viticulture in the south of France, climate change will have a large impact on soil in this region, which also affects viticulture indirectly. Figure 2 displays information from the European Soil Database, showing the predominant soils in southern France. The three most widespread soils are cambisols, leptosols, and fluvisols. Luvisols are also found here, but to a slightly lesser extent. Cambisols and leptosols are the most and third most widespread soils in the entire Mediterranean Basin respectively (Allam, 2020). Luvisols are also the fourth most widespread soils in the Basin (Allam, 2020). Fluvisols are soils that are typically found in relatively flat areas in terms of topography. They are also frequently flooded by surface water or rising groundwater, so river floodplains, deltas, and coastal areas are where they can usually be found (Allam, 2020). All of these soils have been shown to be ideal for viticulture, with the exception of fluvisols, as they contain the correct mineral supply, moisture content, and temperature for the successful cultivation of grapevines. However, as climate change continues to affect the planet, especially the Mediterranean Basin, these soils are at risk. Erosion, overheating, and oversaturation of soils in certain areas are a few of the forthcoming consequences that will present challenges for viticulture.

i. Soil Erosion

Soil erosion is a primary concern for grape growers. It has already affected many French wine-producing regions by wearing away suitable land. In the Languedoc-Roussillon region, 19% of surfaces have been lost due to erosion (Alonso Ugaglia et al. 2019). The combined Rhone Valley and Provence region has also lost 11% of its surface due to erosion. This trend has been seen in many other French wine regions, such as Corsica, the Loire Valley, Bordeaux, and

Burgundy, but to a lesser extent. On the other hand, a few areas have actually gained surface area from erosion, including the northern regions of Champagne, Alsace, and Charentes-Cognac (Alonso Ugaglia et al. 2019). Soil erosion can be exacerbated by extreme precipitation events and changes in temperature, solar radiation, and atmospheric C02 concentrations which are all projected to increase due to global climate change (Nearing et al. 2004).

Focusing on the Languedoc-Roussillon, Provence and Rhone Valley regions, soil erosion has and continues to pose a large threat to grape cultivation and wine production. Vineyards located on leptosol soils are the most at risk, as leptosols are typically very shallow and sloping, making them extremely susceptible for erosion (Zdruli et al. 2010). Leptosols are present throughout all three viticultural regions in the south of France (Figure 2). Terracing is a strategy that has been and must continue to be employed on lands with leptosol soils to prevent destructive erosion. Luvisols are also moderately susceptible to erosion, especially those on sloping areas. Coincidentally, it has been found that luvisols can produce very high quality wine grapes in these sloping areas that are usually terraced (Zdruli et al. 2010). Figure 2 shows that luvisols are mostly present in the Languedoc-Roussillon region, north of the Spanish border, north and west of Perpignan. Therefore, these vineyards are at highest risk of surface loss due to soil erosion.

It is also important to note that vineyards in this location are also predicted to experience an increase in volumetric soil water content (Figure 11d). The combination of erosion-susceptible soils in this area and increased VSW content may cause more land loss due to soil instability and resulting movement. Although it is predicted that there will be a decrease in annual precipitation on vineyards in this location (Figure 11b), soil erosion is still a likely outcome as there will be decreased biomass production due to lack of precipitation, rendering land more susceptible to erosion (Nearing et al. 2004). However, grape growers' response to these changes can potentially minimize damage to viticulture if enacted at the right time and correctly (Nearing et al. 2004).

ii. Soil Temperature

Viticulture is dependent upon soil temperature, especially in the vine's root zone, in addition to air temperature. Factors such as soil color, albedo (amount of sunlight reflected by soil), slope steepness/direction and water content determine soil temperature (van Leeuwen et al. 2018). Soil temperature, like air temperature, can affect grapevine phenology, causing accelerated or decelerated development stages which alter grape flavor. Cooler soils can slow grape growth stages to later in the growing season, whereas warmer soils allow these stages to occur sooner (van Leeuwen et al. 2018).

As Figure 11 (a) shows, southern French vineyards are predicted to experience an increase in average annual temperature. The northern mountainous areas of the Rhone Valley region are expected to experience a particularly large change, with up to an 18-degree Celsius increase in average annual temperature. These two regions are also predicted to experience a decrease in volumetric soil water content (Figure 11d). The combination of these two predicted changes will likely cause an increase in soil temperature on these vineyards located in mountainous areas of the Rhone Valley.

Furthermore, cambisols and leptosols are the predominant soil types in this area of the region, with some fluvisols present as well. Cambisol soils are high in organic matter, as well as clay, aluminum, and iron, which has been found to affect its thermal properties which regulate soil heat balance under different land use regimens (Doneva et al. 2022). Therefore, it can be predicted that vineyards on cambisol soils in the northern Rhone Valley region will experience increase in soil temperature due to climate change, which will result in altered phenology of grapevines.

iii. Soil Nitrogen Content

Lastly, it is likely that climate change will affect the nitrogen content of soils on southern French vineyards. Soil nitrogen is an important factor in viticulture, as it affects grape vine vigor, size of the grape yield, individual grape size, sugar content, acidity and aromas (van Leeuwen et al. 2018). Soil nitrogen levels may decrease by the year 2050 due to denitrification or soil erosion (John A. Lamb 2014).

Soil denitrification is most likely to occur on soils that have been saturated for 2 to 3 days. Therefore, vineyard areas that are predicted to experience an increase in VSW content by 2050 or are located on poorly drained soils are most susceptible to potential denitrification. Since southern Languedoc vineyards will experience an increase in VSW content, they are more likely to experience decreases in vine vigor, size of the grape yield, individual grape size, acidity, and aromas. Vineyards existing on cambisols are at high risk of denitrification, as cambisols in this region are poorly drained, which can be identified by their reddish, redoximorphic appearance (ISRIC). Conversely, vineyards existing on leptosols and luvisols are not at high risk of soil denitrification, as leptosols have excessive internal drainage allowing them to stay relatively dry and luvisols are also generally well-drained in this region (refer to Figure 2) (ISRIC).

Denitrification is also more common in soils with ample organic matter in the top soil layers (John A. Lamb 2014). Cambisols are typically high in organic matter, so many vineyards in the south of may experience denitrification as the result of a combination of high organic matter and saturation. France’s southern Languedoc-Roussillon vineyards could be the most at risk for denitrification, negatively impacting viticulture, as they are mainly situated on cambisols which are both high in organic matter *and* poorly drained, as well as the fact that they are projected to experience the largest increase in VSW in layer 1. There are also some northern vineyards in the Rhone Valley that are projected to experience an increase in total annual precipitation in 2050, which may cause soil oversaturation and result in denitrification.

Soil nitrogen can also be lost through soil erosion (John A. Lamb 2014). Although these losses are small when compared to other ways in which nitrogen can be lost, it is important to consider when studying the future of Mediterranean viticulture. Since the southern French wine regions are highly susceptible to soil erosion, this makes them susceptible to soil nitrogen loss as well.

There is also the possibility of an increase in soil nitrogen content on some southern French vineyards by 2050, since nitrification occurs at a high rate in warm, moist, well aerated soils (John A. Lamb 2014). Soils in the Northern Rhone Valley and Provence may become higher in nitrogen content since they will experience the biggest increase in average annual temperature by 2050 (Figure 11a). If soil nitrogen levels become too high in these areas, grapes are susceptible to rot, rendering them completely unusable for the production of wine (van Leeuwen et al. 2018).

Conclusion

Downscaled climate projections in southern France show that there will be significant changes in average annual temperature, total annual precipitation, and average length of dry spells by the year 2050, according to the RCP 4.5 projection. There will also be minor changes in volumetric soil water content in this region. As a result, the three wine-producing regions in the south of France, Languedoc-Roussillon, Provence, and the Rhone Valley will be faced with challenges in the cultivation of wine grapes, *Vitis vinifera*. The increase in average annual temperature will largely affect grapevine phenology, allowing grapes to reach veraison too quickly. Ripening grapes will then exist on vines for too long, developing more sugars, higher alcohol content, and lower levels of acidity. These characteristics will decrease the quality of the wine produced by these grapes. Higher temperatures throughout the growing season will also reduce grape color due to an inhibition of anthocyanin biosynthesis. Rich grape color is desired for high quality wine, so this is another negative consequence of increased temperatures. Furthermore, grape yields from southern French vineyards will change due to projected changes in precipitation, dry spells, and volumetric soil water content. The decrease in total annual precipitation and increase in length of droughts on vineyards by 2050 may cause water stress to grapevines, decreasing the number of grapes grown due to impaired photosynthesis and shoot growth. On the other hand, some of the southernmost coastal vineyards will experience an increase in volumetric soil water content despite these precipitation and dry spell trends. This is likely due to the increased likelihood of extreme precipitation events or to sea level rise. This increase in VSW may lead to oversaturation of vineyard soils during rain events, negatively impacting grape skin phenolic compounds that produce grape aromas. On the other hand, grapes grown on vineyards in the Provence region will maintain quality aromas, as volumetric soil water content will remain lower in this area. This study also indicated that climate change will affect soils in the south of France, indirectly affecting viticulture. Soils will likely experience higher rates of erosion, higher soil temperatures, and shifts in nitrogen content as the result of changing climate variables. Soil erosion will result in a loss of land suitable for viticulture and thereby a decrease in grape yields. Higher soil temperatures due to the combination of warmer annual air temperatures and high soil organic matter content will affect grapevine phenology similarly to air temperature. Lastly, soil nitrogen contents may increase or decrease to unideal levels as the result of changes in temperature, precipitation and VSW projections. Decreased soil nitrogen will decrease vine vigor, total grape yield, individual grape size, aroma quality, whereas excessive soil nitrogen may cause grapes to rot.

Future Action & Possible Solutions

As these projected changes in the climate and soil occur in coming years, it will become more and more important for grape growers to adjust their viticultural practices to account for new climate norms. To maintain the production of high-quality wines, different grape varieties may need to be planted and cultivated. It is crucial that these new varieties are more resistant to warmer temperatures, droughts, and soil saturation. However, the extremely variable nature of climate change makes this a complicated task, as long periods of heat and drought may be followed by unpredictable extreme precipitation events or frosts. Therefore, grape growers will not be able to simply shift their cultivation to primarily warm weather- and dry-loving grape varieties (Wilcox 2022).

A possible solution to this conundrum is for vineyards to grow many different grape varieties. Each Old-World wine country grows hundreds of different grape varieties, and it is possible to replicate this wide variety on a smaller scale, such as a single vineyard. Growing numerous grape varieties on a single vineyard can allow winemakers more flexibility during harvest, as they can pick and choose which varieties have responded best to the climate conditions of that particular season. This accounts for variability in climate from season to season, as certain grapes will thrive in some years based on the climate conditions and others will not. If there are enough grape varieties planted, winemakers will have the ability to pick and choose those which have grown most successfully to be used in the making of wine for that vintage, or season.

This strategy of expansion in cultivated varieties has already begun in the southern French wine regions studied in this project. Marselan, Caladoc, and Couston varieties have recently been introduced to the region and approved as blending grapes. These species are known to mature later in the growing season, thrive in drought, and provide rich colors (Wilcox 2022). Blending these new varieties with those that have been grown in the region traditionally will become a more common practice and necessary for the continuation of high-quality wine production.

There are numerous other agricultural strategies that can be implemented on vineyards in the attempt to mitigate the negative impacts of climate change on grapes in the future. For example, there are methods to minimize soil erosion, such as implementing terracing and engineered systems that protecting the vineyard land itself from degradation. Another strategy is changing the orientation of vine rows to limit the amount of sun exposure and thus, heat, that the vines receive. More extensive irrigation and canopy manipulation to provide shading may also become necessary to maintain ideal temperatures and water availability for grape growth. Often, a combination of strategies will provide better results on vineyards in the wake of climate change (Naulleau 2020). Lastly, it is critical to acknowledge that viticulture differs immensely across the globe and climate change will affect all viticultural regions uniquely. Therefore, it will be necessary to identify and implement management strategies that are appropriate for a specific region and its viticultural needs.

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Appendix

Detailed Methods and Steps for Map Creation in ArcGIS Pro

Figure 1:

1. Download Copernicus Corine Land Cover vector data (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download)
2. Unzip downloaded data file
3. In ArcGIS Pro, open new map with two automatically added base maps: World Topographic Map and World Hill shade
4. Add Data: France shapefile
5. Add Data: newly downloaded Copernicus Corine Land Cover of Europe
6. Select data by attributes. Choose vineyard land cover, ID=221.
7. Select vineyard land cover data by location for wine regions to focus on, including the following regions: Languedoc Roussillon, Provence, and the Rhone Valley
8. Symbolize vineyard areas with one color across all polygons
9. Add another map layout
10. Add Data: France shapefile
11. Add both maps to a new layout file
12. Select extent range on map of France to show area of focus on southern French vineyards
13. Add legend, scale bar, and north arrow to the final map layout

Figure 2:

1. Download ESDAC: European Soil Database v2.0 (vector and attribute data) from: https://esdac.jrc.ec.europa.eu/content/european-soil-database-v20-vector-and-attribute-data
2. Unzip downloaded data file
3. Downloaded corresponding Symbology from LYR Legend File: WRB-LEV1
4. Attached source data (SGDB_PTR.shp) to symbology layer file (WRB-LEV1)

5. Add Data: France shapefile
6. Mask Soil Data everywhere except for France shapefile
7. Add map to Layout file
8. Zoom in to area of interest displayed in Figure 1
9. Add legend, scale bar and north arrow to the final map layout

Data Reference:

The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004.

Southern French Vineyards Raster Layer (to be used in Figures 3-10):

1. Download Copernicus Corine Land Cover raster layer (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download)
2. Unzip file and open a new ArcGIS Pro file
3. Add Data: Corine Land Cover raster data
4. Use Data Management Tool: Clip Raster
    1. Input Raster: Corine Land Cover raster
    2. Output Extent: Southern France Vineyards shapefile from Figure 1
    3. Select Use Input Features for Clipping Geometry
    4. Run tool
5. Change pixel values of new clipped raster by using Spatial Analyst Tool: Reclassify
    1. Make all raster values = 1 and everything else = NoData
    2. Run tool

Figure 3 and 4:

1. On Copernicus.eu, navigate to “Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections”: https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-biodiversity-cmip5-regional?tab=form
2. In the “Download Data” tab, select the following data:

    1. Region: Europe
    2. Variable: Bioclimatic indicators as in WORLDCLIM: Annual mean temperature (BIO01)
    3. Derived Variable: Annual mean
    4. Model: IPSL-CM5A-LR (IPSL, France)
    5. Ensemble Member: r1i1p1
    6. Experiment: RCP4.5
    7. Statistic: Mean
    8. Version: 1.0
    9. Format: Zip file
3. Download and unzip the selected data
4. Save as NetCDF file
5. Open new ArcGIS Pro map, two basemaps are automatically added: World Topographic Map and World Hillshade
6. In Toolbox, use Geoprocessing Tool: Make NetCDF a Raster Layer
    1. In the Value drop down, select Time
        1. When making Figure 3, make Time = 2020-01-01T00:00:00
        2. When making Figure 4, make Time = 2050-01-01T00:00:00
    2. Click Run
7. Once the raster has been added to the map, use Spatial Analyst Tool: Raster Calculator to apply a conversion factor to the raster data
    1. Subtract - 273.15 from raster data to convert values from Kelvin to Celsius
8. Add Data: France shapefile
9. Use Data Management Tool: Clip Raster to create a new raster with values within the France shapefile
10. Select clipped raster and go to Appearance tab
    1. Under Symbology, select Classify
    2. Use 5 classes constructed by Jenks Natural Breaks and select color scheme
11. Add Data: Southern French Vineyards raster layer (all pixel values = 1)
12. Use Spatial Analyst Tool: Raster Calculator

    1. For Figure 3, multiply 2020 French Mean Annual Temperature raster layer by Southern French Vineyards raster layer
    2. For Figure 4, multiply 2050 French Mean Annual Temperature raster layer by Southern French Vineyards raster layer
    3. Run tool
13. Select newly multiplied raster layer and use Spatial Analyst Tool: Sample to create a table containing all of the newly multiplied pixel values
14. Right-click Sample table in Contents Pane and select Data > Export Table
    1. Add .txt to Output name to create a new text file of data
    2. Click Run to acquire a file containing all pixel values from 2020 or 2050 Mean Annual Temperature on Southern France Vineyards

Data References:
Figure 3:
Wouters, H., Berckmans, J., Maes, R., Vanuytrecht, E., De Ridder, K. (2021): Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections, version 1.0, (for [2020], [Europe], [IPSL-CM5A-LR], [r1i1p1], [RCP 4.5] etc). Copernicus Climate Change Service (C3S) Climate Data Store (CDS), (Accessed on 21-NOV-2022), DOI: 10.24381/cds.0ab27596

Figure 4:
Wouters, H., Berckmans, J., Maes, R., Vanuytrecht, E., De Ridder, K. (2021): Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections, version 1.0, (for [2050], [Europe], [IPSL-CM5A-LR], [r1i1p1], [RCP 4.5] etc). Copernicus Climate Change Service (C3S) Climate Data Store (CDS), (Accessed on 21-NOV-2022), DOI: 10.24381/cds.0ab27596

Figure 5 and 6:

1. On Copernicus.eu, navigate to “Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections”: https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-biodiversity-cmip5-regional?tab=form
2. In the “Download Data” tab, select the following data:
    1. Region: Europe
    2. Variable: Bioclimatic indicators as in WORLDCLIM: Annual precipitation (BIO12)
    3. Model: IPSL-CM5A-LR (IPSL, France)
    4. Ensemble Member: r1i1p1

    5. Experiment: RCP4.5
    6. Statistic: Mean
    7. Version: 1.0
    8. Format: Zip file
3. Download and unzip the selected data
4. Save as NetCDF file
5. Open new ArcGIS Pro map, two basemaps are automatically added: World Topographic Map and World Hillshade
6. In Toolbox, use Geoprocessing Tool: Make NetCDF a Raster Layer
    1. In the Value drop down, select Time
        1. When making Figure 5, make Time = 2020-01-01T00:00:00.
        2. When making Figure 6, make Time = 2050-01-01T00:00:00
    2. Click Run
7. Once the raster has been added to the map, use Spatial Analyst Tool: Raster Calculator to apply a conversion factor to the raster data
    1. Multiply raster data by 3600 x 24 x 365 x 1000 to convert values from annual mean of the daily mean precipitation rate to millimeters per year
8. Add Data: France shapefile
9. Use Data Management Tool: Clip Raster to create a new raster with values within the France shapefile
10. Select clipped raster and go to Appearance tab
    1. Under Symbology, select Classify
    2. Use 5 classes constructed by Jenks Natural Breaks and select color scheme
11. Add Data: Southern French Vineyards raster layer (all pixel values = 1)
12. Use Spatial Analyst Tool: Raster Calculator
    1. For Figure 5, multiply 2020 French Annual Precipitation raster layer by Southern French Vineyards raster layer
    2. For Figure 4, multiply 2050 French Annual Precipitation raster layer by Southern French Vineyards raster layer
    3. Run tool

13. Select newly multiplied raster layer and use Spatial Analyst Tool: Sample to create a table containing all of the newly multiplied pixel values
14. Right-click Sample table in Contents Pane and select Data > Export Table
    1. Add .txt to Output name to create a new text file of data
    2. Click Run to acquire a file containing all pixel values from 2020 or 2050 Annual Precipitation on Southern France Vineyards

Data References

Figure 5:

Wouters, H., Berckmans, J., Maes, R., Vanuytrecht, E., De Ridder, K. (2021): Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections, version 1.0, (for [2020], [Europe], [IPSL-CM5A-LR], [r1i1p1], [RCP 4.5] etc). Copernicus Climate Change Service (C3S) Climate Data Store (CDS), (Accessed on 21-NOV-2022), DOI: 10.24381/cds.0ab27596

Figure 6:

Wouters, H., Berckmans, J., Maes, R., Vanuytrecht, E., De Ridder, K. (2021): Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections, version 1.0, (for [2050], [Europe], [IPSL-CM5A-LR], [r1i1p1], [RCP 4.5] etc). Copernicus Climate Change Service (C3S) Climate Data Store (CDS), (Accessed on 21-NOV-2022), DOI: 10.24381/cds.0ab27596

Figure 7 and 8:

1. On Copernicus.eu, navigate to “Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections”: https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-biodiversity-cmip5-regional?tab=form
2. In the “Download Data” tab, select the following data:
    1. Region: Europe
    2. Variable: Drought Indicators: Dry Spells
    3. Derived Variable: Mean length with minimum 5 days
    4. Model: IPSL-CM5B-LR (IPSL, France)
    5. Ensemble Member: r1i1p1
    6. Experiment: RCP4.5
    7. Statistic: Mean
    8. Version: 1.0
    9. Format: Zip file
3. Download and unzip the selected data

4. Save as NetCDF file
5. Open new ArcGIS Pro map, two basemaps are automatically added: World Topographic Map and World Hillshade
6. In Toolbox, use Geoprocessing Tool: Make NetCDF a Raster Layer
    1. In the Value drop down, select Time
        1. When making Figure 7, make Time = 2020-01-01T00:00:00
        2. When making Figure 8, make Time = 2050-01-01T00:00:00
    2. Click Run
7. Add Data: France shapefile
8. Use Data Management Tool: Clip Raster to create a new raster with values within the France shapefile
9. Select clipped raster and go to Appearance tab
    1. Under Symbology, select Classify
    2. Use 5 classes constructed by Jenks Natural Breaks and select color scheme
10. Add Data: Southern French Vineyards raster layer (all pixel values = 1)
11. Use Spatial Analyst Tool: Raster Calculator
    1. For Figure 7, multiply 2020 French Mean Length of Dry Spells raster layer by Southern French Vineyards raster layer
    2. For Figure 8, multiply 2050 French Mean Length of Dry Spells raster layer by Southern French Vineyards raster layer
    - c. Run tool
12. Select newly multiplied raster layer and use Spatial Analyst Tool: Sample to create a table containing all of the newly multiplied pixel values
13. Right-click Sample table in Contents Pane and select Data > Export Table
        1. Add .txt to Output name to create a new text file of data
        2. Click Run to acquire a file containing all pixel values from 2020 or 2050 Mean Length of Dry Spells on Southern France Vineyards

Data References

Figure 7:

Wouters, H., Berckmans, J., Maes, R., Vanuytrecht, E., De Ridder, K. (2021): Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections, version 1.0, (for [2020], [Europe], [IPSL-CM5B-LR], [r1i1p1], [RCP 4.5] etc). Copernicus Climate Change Service (C3S) Climate Data Store (CDS), (Accessed on 21-NOV-2022), DOI: 10.24381/cds.0ab27596

Figure 8:

Wouters, H., Berckmans, J., Maes, R., Vanuytrecht, E., De Ridder, K. (2021): Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections, version 1.0, (for [2050], [Europe], [IPSL-CM5B-LR], [r1i1p1], [RCP 4.5] etc). Copernicus Climate Change Service (C3S) Climate Data Store (CDS), (Accessed on 21-NOV-2022), DOI: 10.24381/cds.0ab27596

Figure 9 and 10:

1. On Copernicus.eu, navigate to "Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections": https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-biodiversity-cmip5-regional?tab=form
2. In the "Download Data" tab, select the following data:
    1. Region: Europe
    2. Variable: Soil Indicators: Volumetric soil water (layer 1)
    3. Derived Variable: annual mean
    4. Model: IPSL-CM5A-LR (IPSL, France)
    5. Ensemble Member: r1i1p1
    6. Experiment: RCP4.5
    7. Statistic: Mean
    8. Version: 1.0
    9. Format: Zip file
3. Download and unzip the selected data
4. Save as NetCDF file
5. Open new ArcGIS Pro map, two basemaps are automatically added: World Topographic Map and World Hillshade
6. In Toolbox, use Geoprocessing Tool: Make NetCDF a Raster Layer
    3. In the Value drop down, select Time
        1. When making Figure 9, make Time = 2020-01-01T00:00:00
        2. When making Figure 10, make Time = 2050-01-01T00:00:00

        Click Run
7. Add Data: France shapefile

8. Use Data Management Tool: Clip Raster to create a new raster with values within the France shapefile
9. Select clipped raster and go to Appearance tab
    3. Under Symbology, select Classify
    4. Use 5 classes constructed by Jenks Natural Breaks and select color scheme
10. Add Data: Southern French Vineyards raster layer (all pixel values = 1)
11. Use Spatial Analyst Tool: Raster Calculator
    1. For Figure 9, multiply 2020 French Volumetric Soil Water raster layer by Southern French Vineyards raster layer
    2. For Figure 10, multiply 2050 French Volumetric Soil Water raster layer by Southern French Vineyards raster layer
    3. Run tool
12. Select newly multiplied raster layer and use Spatial Analyst Tool: Sample to create a table containing all of the newly multiplied pixel values
13. Right-click Sample table in Contents Pane and select Data > Export Table
    1. Add .txt to Output name to create a new text file of data
    2. Click Run to acquire a file containing all pixel values from 2020 or 2050 Volumetric Soil Water on Southern France Vineyards

Data References:
Figure 9:
Wouters, H., Berckmans, J., Maes, R., Vanuytrecht, E., De Ridder, K. (2021): Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections, version 1.0, (for [2020], [Europe], [IPSL-CM5A-LR], [r1i1p1], [RCP 4.5] etc). Copernicus Climate Change Service (C3S) Climate Data Store (CDS), (Accessed on 21-NOV-2022), DOI: 10.24381/cds.0ab27596
Figure 10:
Wouters, H., Berckmans, J., Maes, R., Vanuytrecht, E., De Ridder, K. (2021): Downscaled bioclimatic indicators for selected regions from 1950 to 2100 derived from climate projections, version 1.0, (for [2050], [Europe], [IPSL-CM5A-LR], [r1i1p1], [RCP 4.5] etc). Copernicus Climate Change Service (C3S) Climate Data Store (CDS), (Accessed on 21-NOV-2022), DOI: 10.24381/cds.0ab27596

Figures 11 (a)-(d)

1. In a new ArcGIS Pro File, create four individual map layouts to contain the following information: the difference in temperature, precipitation, dry spell length, and VSW content on vineyards between 2020 and 2050.

2. For each map layout add the following data:
    - The previously constructed raster layer (from step 11(a) in construction of Figures 3-10) containing vineyard climate data from 2020
    - The previously constructed raster layer (from step 11(b) in construction of Figures 3-10) containing projected vineyard climate data from 2050
3. Using the Spatial Analyst Tool, Raster Calculator, subtract the 2020 vineyard climate raster from the 2050 vineyard climate raster.
4. A new raster is created showing the difference in each climate variable on vineyards between 2020 and 2050.
5. Symbolize, add titles, and add legends to each map
6. Add all four map layouts to one layout file for comparison

(Same Data Sources as Figures 3-10)