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Master's thesis in Geoinformatics for Urbanised Society (30 ECTS)

Spatial variability of the wine quality and price, and their relationships with climatic and soil variables

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Abstrakt

Pealkiri: Veini kvaliteedi ja hinna ruumiline varieerumine ning nende seosed kliima- ja mullastikunäitajatega

Magistritöö eesmärk oli selgitada välja, kas veini kvaliteedi ning kliima- ja mullastikutingimuste vahel on seos. Uurimustöös kasutatud veiniandmestik saadi veiniajakirjast WineEnthusiast. Kliimamuutujad saadi allikast Wordclim version 2 ja mullastikumuutujad allikast SoilGrids. Viinamarjaistanduste geograafilised andmed geokodeeriti Google API abil. Iga viinamarjaistanduse kohta eraldati globaalsetest andmebaasidest erinevad kliima- ja mullastikunäitajad ning teostati korrelatsioon.

Keskkonnamuutujate (kliima ja mullastik) ja veini kvaliteedi vahel suhet ei leitud. Veini hinna ning kliima- ja mullastikumuutujate vahel tuvastati aga mittelineaarne seos, mis kinnitas varasemate uuringute tulemusi. Töö käigus tuvastati ka parima kvaliteedi ja kõrgeima hinnaga veinide tootmise piirkonnad. Need asusid tuntud veinitootmispiirkondades, kus valmistatakse mainekaid veinisorte.

Võtmesõnad: veini kvaliteet, veini hind, ruumiline analüüs

CERCS kood: P510 Füüsiline geograafia, geomorfoloogia, mullateadus, kartograafia, klimatoloogia

Abstract

Title: Spatial variability of the wine quality and price, and their relationships with climatic and soil variables

The aim of Master Thesis was to understand whether there is a relationship between wine quality and climatic and soil conditions. Wine dataset used for this researched was retrieved from the wine magazine “WineEnthusiast”. Climatic variables were obtained from Wordclim version 2 and soil variables from SoilGrids. The wine quality data was geocoded by using Google API. To achieve the aims of this research the quality and price variables were analyzed in relation to various bioclimatic and soil variables.

Environmental variables (climatic and soil) did not show relationships with the wine quality. However, wine price showed non-linear relationships with both climatic and soil variables which confirmed the results of the previous studies. In addition, spatial patterns of the regions with highest wine quality and price were presented. They are located in well-known wine making regions and produce prestigious types of wine.

Keywords: Wine quality, wine price, spatial analysis

CERCS code: P510 Physical geography, geomorphology, pedology, cartography, climatology

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1 Introduction

With hundreds of wine choices presented to us in shops and restaurants, it can be a difficult task for the average consumer to choose a suitable wine. Restaurants overprice wines knowing that most customers can't tell a wine's true value. On the label, one is presented with the brand, year, and country of origin among other information which is vital to asses a wine's value (Sébastien Lecocqyand, 2003).

One of the main factors influencing the quality of wine is climate (van Leeuwen and Darriet, 2016). The vintage is always depending on the weather throughout a year (Abbal et al., 2019). The quality of grapes is mainly dependent on climatic conditions which can affect their ripeness (Baciocco et al., 2014; Jones et al., 2005). Grapes, which are used for high-quality wine production cannot be grown all over the world. Van Leeuwen and Darriet (2016) describe that the wine growing regions are spread over the 30^{th} and 50^{th} parallels in Northern and Southern Hemispheres. Grapes used for wine production cannot be produced in a zone with too much precipitation or with extreme temperatures in summer and winter, which will ruin the berry composition. For example, if there was more rainy days than usual, it can affect the level of sugar and acid in grapes (Jones et al., 2005).

The other factor, which is affecting the wine quality is soil. Soil is not only physical, but it is also chemical environment. According to Abbal et. al (2019), it contains a lot of elements, which later become the main components in berries. For example, the color of wine depends on anthocyanins, which are also contained in soil. The tannins, contained in the soil affects the grape taste, which, in turn, influences the wine taste (Abbal et al*.,* 2019). Also, some chemical elements, such as Calcium (Ca), Magnesium (Mg), Manganese (Mn) and others are ones of the main components of the wine grape (Blotevogel et al., 2019a). The amount of Ca in Mg in wine grapes depends on the wine color. Higher concentrations of Mg can be found in rosé and red wines, when Ca concentration are lower in these types of wine, but higher in white wines. Ramirés et. al (2019) points out that vineyard soil is an environment for the bacteria and fermentative yeasts, which have an effect on grapes. In the harvesting season, the amount of sugar in rape berries is influenced by the concentration of fermentative yeasts in the soil. Moreover, Carbon composition has an effect on the amount of sugar in wine grapes (Spangenberg and Zufferey, 2018).

Several studies conducted the research on how climate and soil conditions influence quality of wine grapes. It is known that for growing grapes and to produce good wine the specific amount of precipitation, some climatic and soil conditions should be met (Gergaud and Ginsburgh, 2019). A lot of studies show the quality correlation between only climatic or soil variables (Ramos and Martínez

de Toda, 2020; Sáenz-Navajas et al., 2014). Some of them analyze one of the chemical factors, which can affect the grape composition (Spangenberg and Zufferey, 2018). Most of the research papers perform the studies only for a specific country or a wine making region with its own microclimate (Davis et al., 2019; Fourment et al., 2017; Irimia et al., 2018).

In this study the analysis will be performed on a global scale, showing specific results for different continents. The aim of my study is to find out whether there is relationship between wine quality ranking and price, and wine quality ranking and climatic and soil variables. To achieve this, I will analyze over 100 000 wine reviews and find the spatial patterns regarding wine quality and price.

More specific aims:

- To identify the spatial patterns of wine quality and price
- To identify the regions of highest quality and price of wine
- To determine whether there is relationship between wine quality/price and climatic and soil variables

2 Theoretical overview

2.1 Factors affecting wine quality

2.1.1 Climate

The main theoretical background for this study provides the information about the quality of wine. Hu et al. (2016) mention that the approach to determine the quality of wine was always challenging, because it is not easy to identify. The quality of wine depends on many factors such as climate, soil, grape type, etc. The French conception of "terroir" can be explained as a configuration of such factors as soil, climate, topography and vine characteristics of the wine (Blotevogel et al., 2019b). The terroir can explain why the vineyards and wineries are usually located close to each other. They have suitable conditions for wine production such as climate and soil (Lock et al., 2019).

According to Abbal et al. (2019), vintage depends on the weather throughout a year. Its quality comes from various factors: the amount of sunny and rainy days, the temperature, number of windy and hot days, solar radiation Baciocco et al. (2014) point out that cool wet winters and springs, and dry and warm summers are the conditions, where the high-quality wines can be produced.

One of the factors affecting the wine grape quality is the precipitation throughout a year or plant water status (Bonfante et al., 2018). Precipitation is an influential factor of the grape quality, as water is important for the plant in the time of the plant creation, while dry conditions play significant role in the flower development and grape ripening (Merloni et al., 2018).

Baciocco et al. (2014), describe that rain during the formation of berries and ripening period can be the crucial factor and decrease the quality of wine. According to Fayolle et al. (2019), water content is one of the determinants of red wine quality. It plays significant role after the period of plant flowering, when the polyphenols are being synthesized. Those are the elements influencing the red grapes quality, which are used in red wine production. Zsófi et al. (2011) points out that water deficit has an effect on photosynthesis and shoot growth and this has negative effect on a berry size. It was found that larger grapes have lower sugar concentration than the small ones. In addition, the serious water deficit may lead to the leaf damage and prevent the ripening of the berry (van Leeuwen et al. 2016). Although, moderate water deficit has a positive effect on berry and wine quality. The concentration of phenolic components of a grape, such as anthocyanins and tannins, are higher in the regions with moderate water deficit (Zsófi et al., 2011). According to Baciocco et al. (2014), warm and dry conditions during the grape formation and ripening are optimal for development of a balance between sugar and acid levels in berries. Also, the ideal precipitation amount during the wine grape ripening is about 63 mm for high-quality red wines and 48 mm for white wines.

Jones et al. (2005) indicate that, in general, the grapes and the wine which is produced from them, are the result of an overall climate, so the growing season length and temperatures are the critical aspects. More specifically, this has an influence on the ripeness of grapes, of the amount of sugar, acid and flavor. For example, the level of sugar in the grape increases with the temperature, but anthocyanin, which are affecting the wine color are negatively affected by high temperatures (Jones et al., 2005). The suitable air temperature for high-quality sweet white wines throughout the growing season is above 17.3 ˚C, when for the red wines it can vary from 16.4˚C to 18.8 ˚C. Also, the level of malic acid, which is one of the most common in the grapes decreases because of the high temperature (Darriet, 2016; Palma and Barroso, 2002). Orduña (2010) describes that cool climate is suitable for developing the aroma of white wines, when high temperatures can decrease the aromatic intensity. Sun exposure is an important component for generation of fruity, floral and spicy wine aromas. Van Leeuwen and Darriet (2016) point out that it's difficult to separate the temperature and the light. The solar radiation, which is affecting wine grapes is increasing the amount of anthocyanins in berry skin, but high temperatures have negative effect on it.

Also, according to Orduña (2010), the high temperatures about 30 ˚C and higher reduce the berry size and weight. The result of this can be that the metabolic processes and accumulation of sugar can stop. It is also described that the acid level is usually correlated with pH level in berry composition. So, as high temperatures decrease the acidity, the level of pH is being increased. In addition to changes in acid, sugar and pH levels in grape composition, high temperatures together with solar radiation have an effect on the other compounds, which are important for wine color and aroma.

The changes in climate directly affect the wine production. Ubeda et al. (2020) indicate that wine production depends on grape and this berry is very sensitive to climatic conditions. Changes in temperature can be one of the main causes of changes in wine region patterns, as the microclimate has bigger effect on grapes than soil conditions. As the grapes will be influenced, this can lead to various plant diseases and consequently, the wine will have different sugar and alcohol content than before (Merloni et al., 2018). Drappier et al. (2019) point out that the temperature is the crucial factor influencing the grapes, so the higher temperatures increase metabolic rates and affect metabolite accumulation. In this case, the growing season is getting longer, harvest happens earlier and the phenological intervals are getting shorter. The observations were made in different countries in Europe such as France, Spain, Germany and, Italy. In all of these countries the phenological events occurred earlier for 6-18 days, which is a result of global warming. According to Orduña (2010), the harvesting date is now on average 2-3 weeks earlier than it was in 20th century. For example, in Alsace region in France the mean annual temperature was increased by 1.8 ˚C, which is plays a significant

role during grape formation and ripening. Also, in Baden, Germany, the temperatures were about 1.2 ˚C higher in the last 10 years.

Discussing the influence of the climate change on wine grape quality, Bonfante et al. (2018) describe that the growing season of the grape should be approximately 170-190 days and the change in average temperature can affect the growing length and quality of the grape. The extreme temperatures during the growing season also affecting the wine production. For example, the temperatures below -2.5 ˚C can freeze some parts of the plant, while high temperatures above +35 ˚C will have the effect on color development and anthocyanin production.

Alikadic et al. (2019) point out that the faster plant growing will influence the grape quality. Phenological phase length and growing season influence the time the plants need to produce sugars. Due to this fact there can be changes in sugar and acid levels, also, wine flavor will be modified by the higher level of the ethanol.

2.1.2 Soil

According to Abbal et al. (2019) soil is another direct factor, affecting the quality of wine. It represents both the physical and chemical environment. Soil can change the wine compound through affecting the wine grape plant with mineral components contained in soil (Blotevogel et al., 2019b). Gergaud et al. (2019) point out that not all grapes grow in every region because of many factors and one of them is soil. Abbal et al. (2019) mention that the soil components such as sand, clay, limestone and humus, chemical and physical components are playing a significant role in wine quality.

Soil characteristics such as nutrients and pH are ones of the main components, which affect the vine growing and wine quality (Fayolle et al., 2019a). Nutrients in soil, such as N, P, Ca, Mg and Fe, and as it is known, Ca is the fourth most important element in wine. The color of wine depends on anthocyanins, which are also contained in soil. The relationship between wine quality and chemical elements in soil varies and depends on plant physiology and the water availability in soil (Fayolle et al., 2019a). In the compounds of the red wine, there is a higher concentration of Mg, rather than white or rosé wines (Blotevogel et al., 2019b). The tannins, contained in the soil affects the grape taste, which, in turn, influences the wine taste. Moreover, tannins in combination with anthocyanins control the color stability. There are many other soil characteristics such as pH, Ca/Mg ratios and others which affect the grape quality, so the soil is one of the main factors on which the quality of wine depends.

According to Cravero (2019), nowadays, the trend of organic wine is globally increasing. This is the wine without sulphites and can be considered as a vegan and vegetarian wines. The production of this

kind of wine is reducing the chemical fertilizers and pesticides, which can be used in the creation of wine production. Also, this type of wine can be only produced from organic grapes without any additives and adjuvants. It was discovered that the acid level in the organic wine is higher than in conventional wine. Also, there was a lower pH level and higher level of free anthocyanins and polyphenols in the organic wine.

Slope of the terroir has an effect on the amount of the received solar radiation. Also, slope and soil type of the wine producing region play a significant role in water household of the vineyards (Zsófi et al., 2011).

According to Ramírez et al. (2020), soil can also be the natural environment for the collection of the fermentative grape yeasts, which comes from the damaged berries that fall during bad weather, harvesting period or because of the birds. Nitrogen in wines is presented in an inorganic form component, such as ammonia, nitrate and nitrite anions. But also, it appears in wine in an organic form as amines, amides, amino acids, amino esters and vitamins. Most of these nitrogen compounds are the soil components (Spangenberg et al. 2018). Fayolle et al. (2019) point out that the lack of Nitrogen in soil can improve the quality of the red wine.

Sun et al. (2018) point out that copper is one of the elements in the soil, which can reduce the quality of wine. This metal was used in XVIII century to protect the vines against fungal disease. In addition, the use of copper in winemaking equipment can also have negative effect on the wine quality. As the soil component copper does not move, which leads to its accumulation in vineyard soils and poisoning the berries, it has negative effect on the wine fermentation process as it is delays fermentation and reduces the alcohol construction. Moreover, if the wine with high copper level was produced, it could be dangerous for the health of wine consumers, especially with the combination of other heavy metals.

Although, the quality scores from the wine experts are usually used as a measure for quality of wine, the reviews on the same wine typically differ from different tasters. According to Schiefer et al. (2008) expert ratings are dependent on the year of vintage, terroir, which is soil and climatic conditions of the region. People are different and all of them have different preferences. Cardebat et al. (2016) points out that some of the experts prefer full bodied wines obtained with very mature grapes, when others' choice fell on more astringent wines, when the climate has been colder. So, the expert opinions vary systematically in terms of their preferences. In this way there is no pure and excellent measure for quality of wine (Oczkowski, 2016a). So, in this case, the quality measured by experts is a subjective view.

2.2 Wine price

Discussing the wine prices, Sebastien et al. (2003) describes that the price does not just come from the quality of wine. Nowadays we have hundreds of different wines in the shops and all of them cost differently. Firstly, the price comes from the bottle. If it is a simple and plain bottle, the price for its production can be only $2, but if it is a unique and prestigious wine like Bordeaux Haut-Brion or Grange, for example, the bottle can cost several hundreds of dollars. Also, the features mentioned on the bottle can affect the price. Those are the brand, label, year of vintage, etc. Cardebat et al. (2018) describes that brand name has a significant influence on the price as an objective quality. So, the reputation of the vineyard or winery can be crucial factor in the reasons of the determination of the price. The reputation of the vineyard, wine producing region, the third-party ratings can be used by a consumer to make a choice on the purchase. Wineries with good reputation can sell products with high-quality label, which cost more. Reputation in this case plays more important role than the quality, as it is difficult for consumers to choose wine without tasting it (Ling et al. 2003). According to Brentari et al. (2011), the appearance is an important factor. The more attractive performance will give better results in sales. About 40% of the cost is usually packaging. The price also depends on the market segmentation and on the impact of the different variables, for example, the year of vintage or the production processes. Cardebat et al. (2018) point out that the price of wine is correlated with the macroeconomic determinants and financial variables. For example, there is a relationship between the price and the demand for the wine. Storage time and conditions must be also taken into account. In addition, the transportation costs and the insurance are added to the price of the bottle. Kourtis et. al (2012) also describe that the changes in EU agricultural policies and the globalization of this segment in the international market increases the prices and this trend will be positive in the future.

(Oczkowski, 2016a) points out that the wine price usually grows with the quality ratings. In addition, there are more characteristics describing the wine prices such as the year of vintage, red wine or white, the type of grape, and acid and sugar level. According to Kourtis et al. (2012) the international wine prices closely depend on the microclimate conditions of the wine producing regions.

The wine in restaurants is overpriced. They do this because the consumer usually has no idea how much it should be. Also, even if they think that they know the retail prices, the mark-ups are usually underestimated (Livat et al., 2018). In addition, the mark-up for cheap wines are much more significant than for expensive ones.

Talking more about prices, it was found out that the weather conditions affect both wine quality and then indirectly, the price. Oczkowski (2016b) estimated the relationship between weather and wine prices. From his study it was found out that the harvest rain and the temperature differential have a significantly negative impact on both wine quality and price. The 1˚C increase in temperature reduces

the wine price less than 1%, but if we talk about further increases in temperature, they can influence the price much more, but also the effect depends on the type of wine.

Di Vita et. al (2019) describe that there is a trend nowadays in the organic products worldwide and the organic wine is not an exception. The consumers are willing to buy the wine with organic label on it. Also, the regionality of the organic wine production is an important factor for consumers. It is meaningful for their decision that the wine will be local, so in their perception the wine maker will use local organic products for it. These are additional attributes for the organic wine price and in the study was found out that consumers are willing to pay the higher price for this type of wine nowadays.

According to Oczkovsky (2016), the wine prices depend on both objective and subjective qualities of wine. The models which he used to determine the relationship between quality and price help to make statements about the price impact of objective and subjective quality. The objective quality is weather conditions, soil, vintage. The subjective quality is mostly related to the reviews on wine from the experts. Gokcekus et. al (2019) describe that the wine ratings are the good signs showing the quality of wine as there is a "high convergent validity among ratings of different evaluators." Also, this validity does not depend on such factors as brand, the country of origin or label, but it only depends on the "aesthetic properties of the wine itself." The reviews from wine experts have a classification system, they have a high reliability and can be used for a scientific research. But as it was said before, all people have different tastes and there is no ideal or excellent measure for the wine quality.

2.3 Spatial variability of wine quality

Many studies are describing the spatial variability of wines in different regions (Fourment et al. 2017; Irimia et al. 2018; Gergaud et al. 2019). According to Irimia et al. (2018) the grapes for wines are dependent on the climatic conditions and the climate change is affecting the wine producing regions and the grape variations. As an example, Irimia et al. (2018) writes about the wine production in Mediterranean areas. In the cool regions, there are grapes, which are suitable for white and some varieties of red wines. In the warm regions, there are grapes adapted to warm climate, from which are red table wines are produced. Due to the climate change, nowadays the regions, which were suitable for red wines became suitable for white wines. Fourment et al. (2017) analyzed the change in type of grapes for wine in Uruguay related to the temperature differences in the wine regions. The results showed that the spatial variability of grapes is depending on the microclimate, because the levels of acid, sugar and etc., in the berries were different in various districts of wine region near La Plata River. Similarly, Irmia et al. (2018) determined also the climate effect on the grape variation and found that due to climate change the type of grape for the white wine, which was exclusive to Romania began to grow in Moldova.

In the current thesis I will focus more on European vineyards and therefore will provide here overview of the main European wine regions.

The main wine production regions in Europe are spread over the zones with Mediterranean climate-type by the reason of the availability of the water and suitable temperatures for growing different variables of wine grapes (Ortega-Farias et al., 2019). Alikadic et al. (2019) describes that due to the climate change, the temperatures in the Mediterranean region will rise more than in other parts of the world . This will affect the wine production, which is widely spread all over the territory. Wine industry will need to adapt to new climatic conditions, as this will have an influence on quality and phenological intervals which vary across the wine regions. According to these factors, these regions will need to change the variety of the wine grapes which will be suitable for higher temperatures and will be adapted to certain climatic conditions (Alikadic et al., 2019).

According to Ferretti (2020), the South Tyrol region in Italy is known as a wine producing region. Despite the fact that it is one of the smallest wine growing regions in the country, there is a big number of vineyards producing top wines and growing some types of grapes, which are the most expensive in Italy due to the variability of soils and the topoclimate of the region. This is the microclimate of the vineyard, which is connected to the topography in the region. This factor is one of the characteristics of the vineyard and winery, and it directly influences the wine type and quality. In the region of South Tyrol vineyards are located in the altitudes between 200 m and 1300 m asl, which according to topoclimate of this area, is suitable for the wine grape growing.

Ramos et al. (2020) describes that La Rioja, located in the Northern part of Spain, is one of the regions with the highest wine quality according to the Denomicación de origen calificada, which is the highest wine qualification in Spanish wine regulations. There is a big concentration of vineyards, producing premium wines by the reason of its microclimatic and soil conditions. The soil type in this viticultural region is rich with Ca and clay fraction, but also sand and silt particles are presented. Various types of grapes suitable for producing high-quality wines are presented in La Rioja as the climatic conditions vary due to the elevation differences. Different temperatures affect the acidity level, the amount of polyphenol content and the amount of anthocyanins in the berries. Also, the anthocyanin concentrations are influenced by the water deficit, which is a result of both soil and microclimatic conditions. It was projected that due to the climate change in 2050 the flowering and harvesting period may shift for 10 days and, potentially, the decrease berry acidity level may happen, so the different types of wine grapes can be cultivated in this viticultural region.

Another small viticultural area in Spain is rich with vineyards, producing high-quality wines. It is located in Castille and Léon region in Soria province (Martín Ocaña et al., 2006), The Mediterranean climate with the average temperature of 9-12 ˚C and the temperature of the hottest month from 18-22

˚C provide ideal conditions for growing wine grapes. Soil conditions also influence the quality of wine, produced there. So, soil composition, which consists of clay, limestone and loam, create a suitable chemical and physical environment for wine production. Also, these climatic and soil conditions positively affect the thermal behavior in cellars, where the wine is being aged.

High-quality premium wines are also produced in French vineyards all over the country (Baciocco et al., 2014). Climate in different parts of the country is optimal for cultivation of quality wine grapes. Loire Valley region is one of the biggest viticultural areas in the country. Its climatic conditions with average annual precipitation of 579 mm and mean annual temperature of 12.3 ˚C allow to produce various types of wine such as dry and dessert-style white wines, sparkling wines or red and rosé wines made from Cabernet Sauvignon, Cabernet franc and other types of wine grapes (Goulet et al., 2011). However, according to Sgubin et al. (2018), climate change is slowly affecting all the French viticultural regions. For example, by the end of 21st century the flowering and ripening of the wine grape may shift for almost 20 days for Alsace region, which is located on the East of the country. Also, the spring temperatures in Champagne region may increase by 4 ˚C, which may cause the changes in wine grape types growing there. But not only the increase in temperature can affect the grape formation. Low temperatures during winter can damage the plant and, according to the study, this risk is increasing in the continental viticultural regions, such as Alsace, Champagne or Burgundy and decreasing in the coastal areas close to Atlantic Ocean and Mediterranean Sea. Although, the number of days with extreme cold temperature is slowly decreasing in 21st century, due to the climate change, the risk of the late frost damage in some of French viticultural regions may increase.

Portugal is 11th largest wine producing country in the world, according to Costa et al. (2019). The country is divided to 14 grape wine growing regions, where 12 are on the main land and 2 are on the islands. According to the study, Douro/Porto wine region is the biggest and has unique features and it belongs to UNESCO human heritage vineyard landscape. It is known that the microclimate affects the phenological phases of a plant and due to the climate change the future projections of the changes in wine production in Portugal were made. It was found that different types of wine grape differently depend on the temperature, some are more sensitive to changes than others. The expected growth in temperature will influence the unbalanced wines, they have high alcoholic and low acid levels. Also, due to higher temperatures throughout a year, there could be an adaptation of the different grape wine type, which berries have lower sugar content and higher acid level.

3 Data and Methods

3.1 Study area

The study will be performed all over the globe in the wine producing regions (Fig. 1). The area consists of various complex landscapes with different kinds of microclimate and soil conditions.

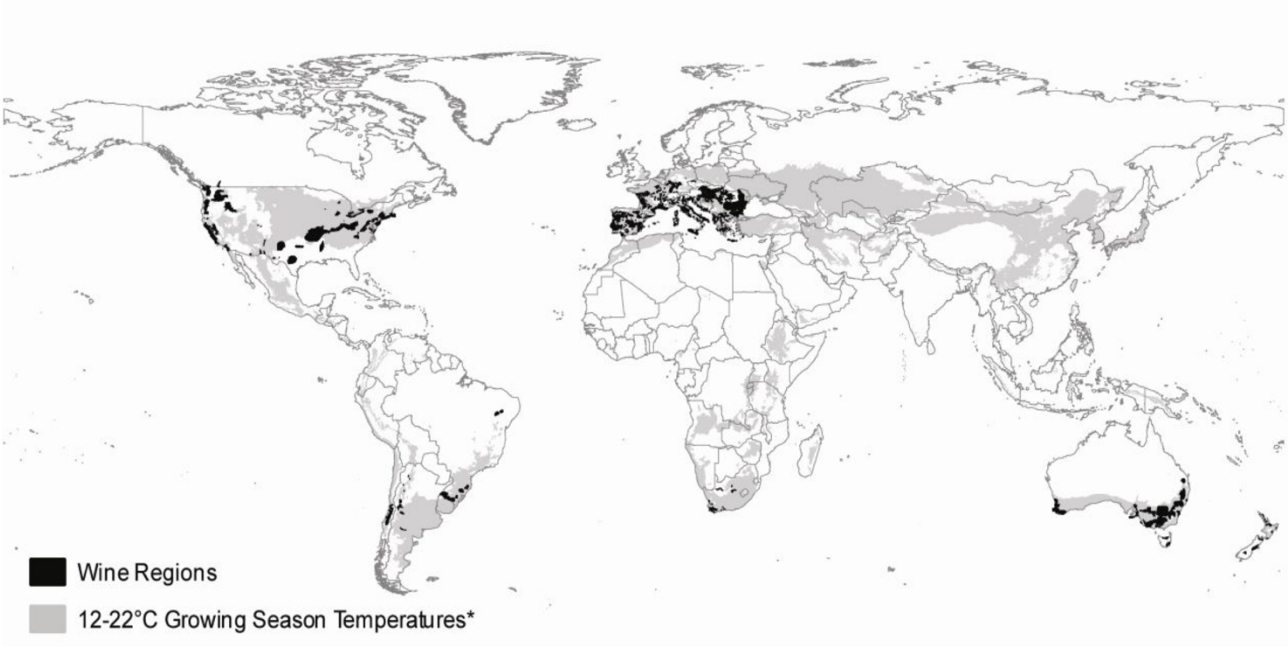

Figure 1. Study area. Source: Jones et al., 2012

The vineyards are concentrated in warm climate zones with minimum air temperature of 10 ˚C and annual precipitation averages from 50-500 mm. In the Mediterranean climate, which is known as a good fit for wine production (Ortega-Farias et al. 2019), summers are dry and hot, winters are rainy and warm.

In this study there is a wide variety of soils with different concentrations of various chemicals such as Ca, Mg, etc., which are the elements affecting the wine quality, color and grape formation (Abbal et al., 2019).

3.2 Datasets

Dataset of the wine reviews

The data of the quality of wine and its price was extracted from the free source: https://www.kaggle.com. The data is originally gathered from wine magazine WineEnthusiast in 2017. The data are available as table in a CSV format. The dataset contains 129 971 rows, each row represents one wine review. The data about wine reviews with location, winery, vineyard, price, points, taster name and taster twitter handle, which can be used to find the expert in Twitter is present.

The data consists of 13 fields in total (Table 1). The variable "Points" represent and used in this study as the wine quality, which is set by the wine reviewers. The quality of wine is rated on a scale 0-100 points, but in this dataset only wines with rating 80-100 are presented,

Table 1. Attribute table of wine dataset

Column name	Data type	Number of non-null values
Country	String	129 908
Description	String	129 971
Designation	String	92 506
Points	Integer	129 971
Price	Float	120 975
Province	String	129 908
Region_1	String	108 724
Region_2	String	50 511
Taster_name	String	103 727
Taster_twitter_handle	String	98 758
Title	String	129 971
Variety	String	129 970
Winery	String	129 971

Climate data

For climate data Wordclim version 2 was used (WorldClim, 2020). The dataset spatial resolution is 30 seconds and it contains 12 GeoTiffs, one for each month of the year 3 historical climatic and 4 bioclimatic variables which are averages for years 1970 – 2000. Bioclimatic variables represent the biologically relevant variables and collected from the monthly temperature and precipitation values. The spatial resolution is quite coarse and does not capture the microclimatic differences that are relevant for the vineyards, however, it is the best available global database that covers all the relevant bioclimatic variables.

According to Bonfante et al. (2018), annual precipitation affects the quality of wine, so the annual trends, which are the annual mean temperature and annual precipitation were extracted. Baciocco et al. (2014), describes that dry and warm summers and wet and cool springs and winters create conditions for the high-quality wine production. Therefore, monthly precipitation and average temperature from the historical climatic variables was extracted. According to Abbal et al. (2019) the vintage depends on the temperature throughout a year. The extreme temperatures during the growing season have an effect on the wine production, as the temperatures below -2.5 ˚C can freeze the plant, when high temperatures over 35 ˚C will stop the anthocyanin production (Bonfante *et al.,* (2018)). So, in this study extreme bioclimatic variables as max temperature of the warmest month, min temperature of the coldest month were used. Monthly solar radiation from the historical climate data

was extracted, as Leeuwen et al. (2016) describe that solar radiation has an effect on the amount of anthocyanins in berry skin.

Soil data

For soil data, global SoilGrids data set was used (SoilGrids, 2020). SoilGrids is a collection of soil property maps for the world which were produced using machine learning with a spatial resolution of 250 meters (Batjes et al., 2020). The predictions of soil properties are presented for 6 depth intervals. SoilGrids uses global models that make use of all available input point data to map a property across the globe. However, as the dataset is largely based on modelling, there are significant uncertainties related to this dataset but currently it is the best available global soil dataset suitable for the current study.

According to Abbal, et al. (2019), soil components such as clay, sand and chemical components have an effect on the quality of wine. Nitrogen and soil pH are important for the plant formation and the lack of Nitrogen can improve the quality of red wine (Fayolle et al., 2019a).

In this study GeoTiffs for soil pH, Nitrogen content, sand content and clay content on the depth of 30-60 cm were used (Table 2). Spatial prediction of the used soil variables is mean. It represents the expected value and represent the neutral prediction of soil property.

Table 2. Soil properties

Name	Description	Mapped units	Conventional units
clay	Proportion of clay particles (< 0.002 mm) in the fine earth fraction	‰	%
PHH2O	Soil pH	pHx10	pH
sand	Proportion of sand particles (< 0.05 mm) in the fine earth fraction	‰	%
Nitrogen	Total Nitrogen (N)	‰	%

3.3 Methodology

3.3.1 Data preprocessing

Data cleaning was performed as first step. Empty values for price and quality, and duplicates were removed from the wine review dataset. After cleaning the dataset, the final dataset contained of approximately 96 000 rows. All the code generated for this study is available in GitHub https://github.com/OlgaWold/Thesis. Data cleaning was performed using Python Pandas.

Price values over 1000$ were checked manually through the Wine-Searcher website (Wine-Searcher, 2020). This site is used to find wine and other alcoholic beverages across online stores. For the price

investigation the year of vintage and wine variety was used. It was found that not all the prices are correct. Some of them were 3-4 times less expensive than in the dataset, so they were excluded.

The variety column in the dataset consists of approx. 600 unique wines. Using it, the wines were manually sorted into 4 categories: Red, White, Rosé and Red/White/ Rosé. The last group contains the wine grape from which all types of wine can be produced. Also, this group includes wine blends, which cannot be classified as Red, White or Rosé alone. approx. 60% of the reviews were for red wine and approx.. 33% for the white wine (Fig. 2).

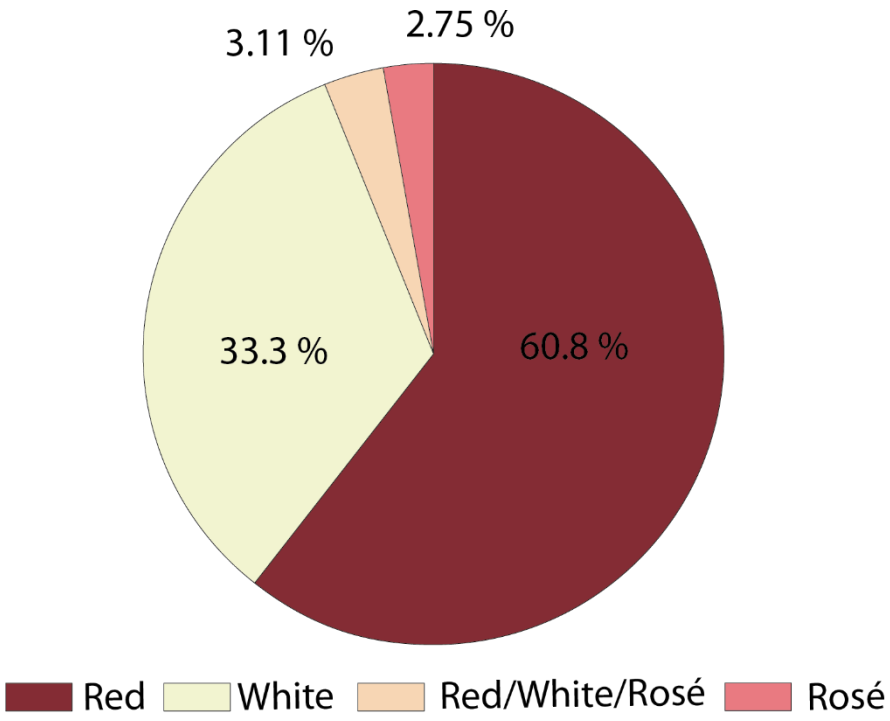

Figure 2. Wines by grape type

3.3.2 Geocoding

Wine dataset did not contain X and Y coordinates, so it was needed to geocode them. Forward geocoding is the process of taking address as text and looking for its latitude and longitude. To optimize the process, firstly the new dataset with only unique vineyards was created from the wine dataset which reduced the number of rows in the dataset from approx. 96 000 rows to approx. 26 000 rows. Each row in the dataset was submitted as a query and coordinates were returned and stored into the "lat" and "long" columns of the attribute table.

To geocode the pair of coordinates, Google API, Mapbox API and OSM API were initially tested. With free access Google provides to process 40 000 rows per month, OSM 2 500 rows per day and Mapbox has an unlimited access. For Google and Mapbox API usage it was necessary to provide

the API key, which is an identifier used to authenticate a user, OSM service was used without any additional parameters. During the test geocoding, it was found that Google is the most precise service and therefore the final geocoding was done using Google API. All data manipulations on this step were performed in Python using Geocoder library. After geocoding, the dataset with the quality and price variables and the new dataset with geocoded coordinates were merged.

3.3.3 Statistical analysis

Preliminary correlation analysis for wine quality/price, and climatic and soil variables was conducted. Assumptions of normality were checked with Anderson-Darling test of normality, as the dataset contains over 96 000 rows and Shapiro-Wilk normality test, which was tried before. Shapiro-Wilk normality test performs test for only 5 000 samples and Anderson-Darling test allows to work with bigger datasets. All the variables have non-normal distribution, as the p-value (level of significance) was lower than 0.05 (Table 3). For assurance in proper correlation analysis type selection, histograms of the variables were created (Fig.3). It is shown that the variables are not normally distributed, therefore, Pearson correlation method was used, as the assumptions of normality were not met.

For correlation analysis between average summer temperature, summer precipitation and quality, the dataset was divided for Northern Hemisphere (NH) and Southern Hemisphere (SH) as summer months are different for them. Dataset for Northern hemisphere consists of approx. 86 000 rows and for Southern hemisphere 10 000 rows.

Before performing correlation analysis, the dataset was checked and unusual values for Annual mean temperature, Average summer temperature in SH, Clay content, Nitrogen content, Sand content and soil pH were removed.

For correlation analysis for wine quality and price, the price data was divided into 3 groups: Cheap wines from 0-20$ (38.1% of data); Mid-priced wines 21-100$ (58.8% of data); Expensive wines 101-2500$ (3.1% of data)

Table 3. Results of the Anderson-Darling normality test

Variable	p-value
Price	< 0.001
Review points	< 0.001
Annual mean t˚	< 0.001
Annual precipitation	< 0.001
Annual solar radiation	< 0.001
Max t˚ of the warmest month	< 0.001
Min t˚ of the coldest month	< 0.001
Average summer t˚ in NH	< 0.001
Average summer t˚ in SH	< 0.001
Summer precipitation in NH	< 0.001

Summer precipitation in SH	< 0.001
Soil pH	< 0.001
Clay content	< 0.001
Nitrogen content	< 0.001
Sand content	< 0.001

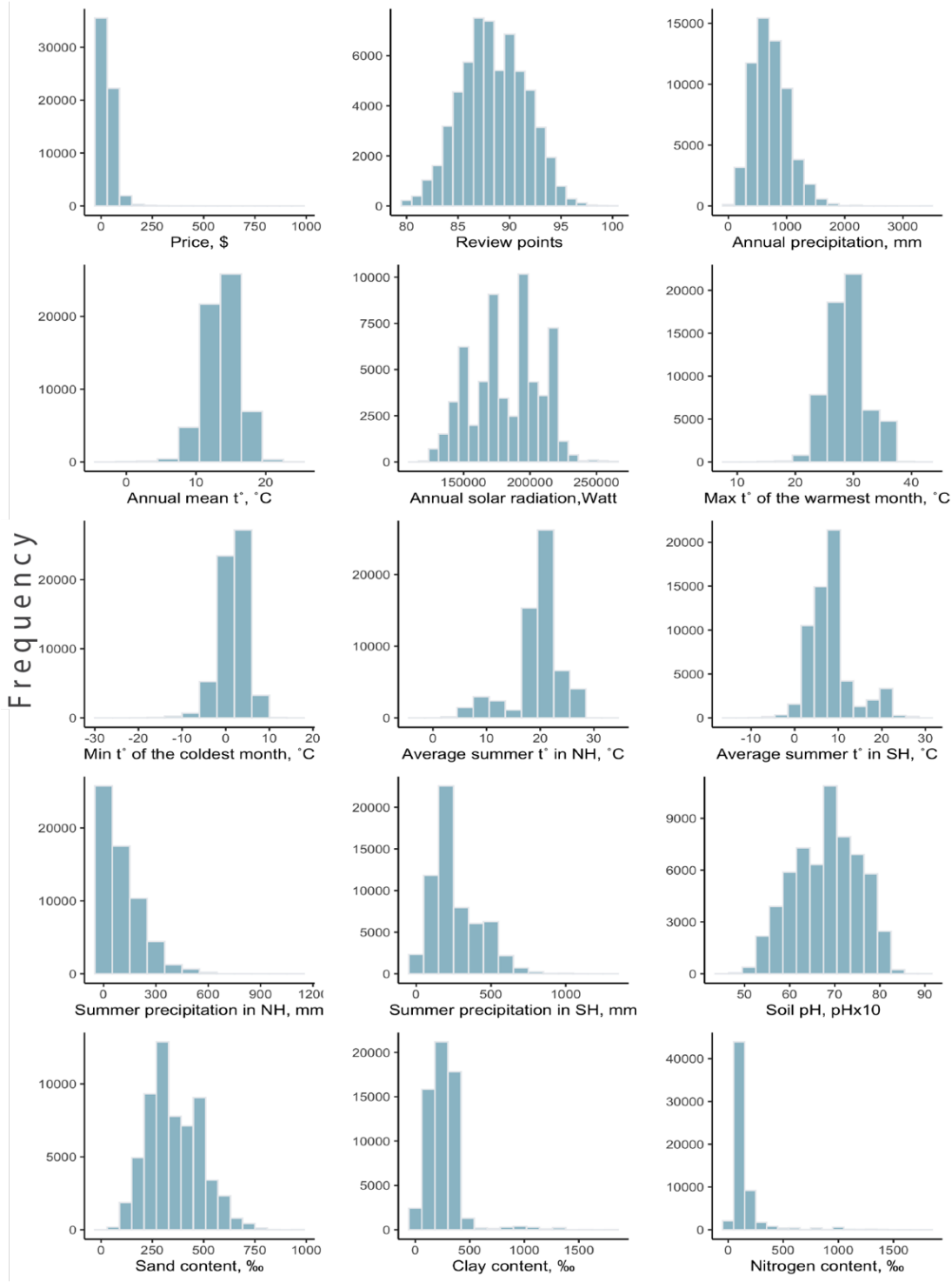

Figure 3. Histograms for: a) price; b) review points; c) annual precipitation; d) annual mean t° ; e) annual solar radiation; f) max t° of the warmest month; g) min t° of the coldest month; h) average summer temperature in the NH; i) average summer temperature in the SH; j) summer precipitation in the NH; k) summer precipitation in the SH; l) Soil pH; m) Sand content; n) Clay content; o) Nitrogen content

3.3.4 Spatial analysis

To identify the spatial patterns and detect the territories with highest quality and price values, the spatial analysis was implemented. The hexagonal grid with polygon area of 600 square km for Europe, North and South America, Australia and Oceania was created. Data aggregation into hexagons and the statistical analysis with calculation of "mean" and "standard deviation" values for wine quality, price and quality-price ratio was implemented with the "Join attributes by location (Summary)" in QGIS. This algorithm calculates a statistical summary for the matching features.
In addition, one country was also analyzed more in depth and Spain was chosen as one of the main wine-producing countries in Europe. The hexagonal grid with area of 100 square km was created and the same statistical calculations as for Europe and other territories were done.
To calculate quality-price ratio, the data was normalized in R-Studio with formula:

$zi = \frac{xi - \min(x)}{\max(x) - \min(x)}$, where $x=(x_1,...,x_n)$ and z_i is i_{th} normalized data.

The ratio was calculated as:

$$ratio = \frac{review\ points}{price}$$

The ratio high values mean that the quality and price rate is better for the consumer, as the wine quality is high and the prices are lower. Low values show that the wine prices are higher, when the quality is low.

Lower values for the "standard deviation" mean that the data is assembled around the mean value, so the variance in the hexagon is low and the wine quality and price in this area are stable and do not change much. Higher values show that the data is more dispersed, so there is a big difference in price and wine quality in the polygon.

4 Results and discussion

4.1 Spatial patterns of wine reviews and prices

For the visualization purposes, wine reviews were aggregated into 15,000 square km hexagons (Fig. 4). The number of reviews was highest on the west coast of USA. Also, big numbers of reviews are coming from known wine producing countries, such as Spain, France, Portugal, Italy, Argentina.

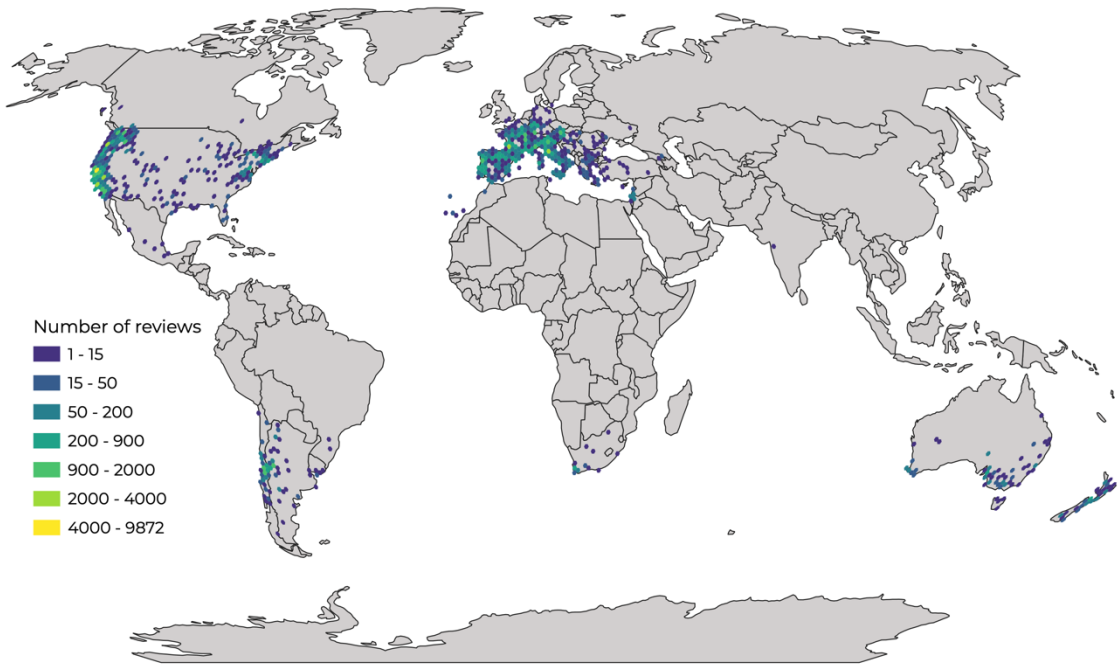

Figure 4. Number of wine reviews

Observing the total number of the wine reviews based on country of wine origin, it was found out that the largest percentage of reviews (about 50%) was made in the USA (Fig. 5). The countries with the biggest number of the unique vineyards and unique wines are known for the producing high-quality wines. These are USA, Spain, France, Australia and etc. (Fig. 6 b).

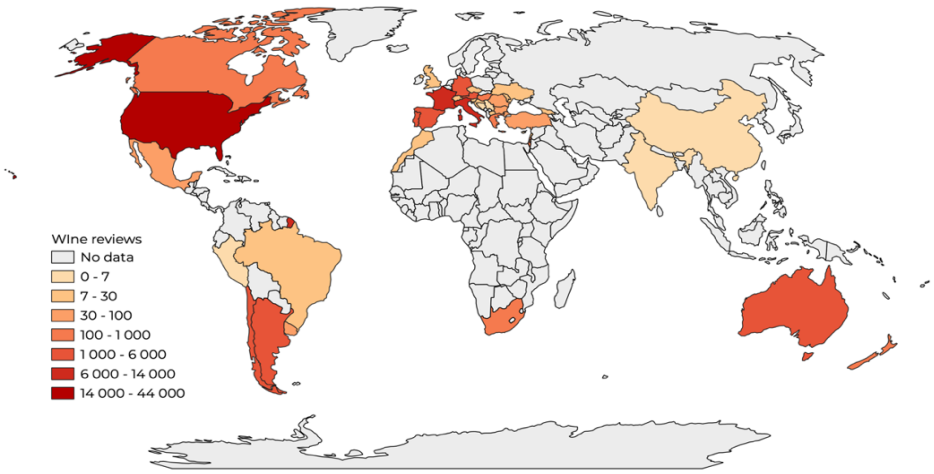

Figure 5. Number of wine reviews per country of wine origin

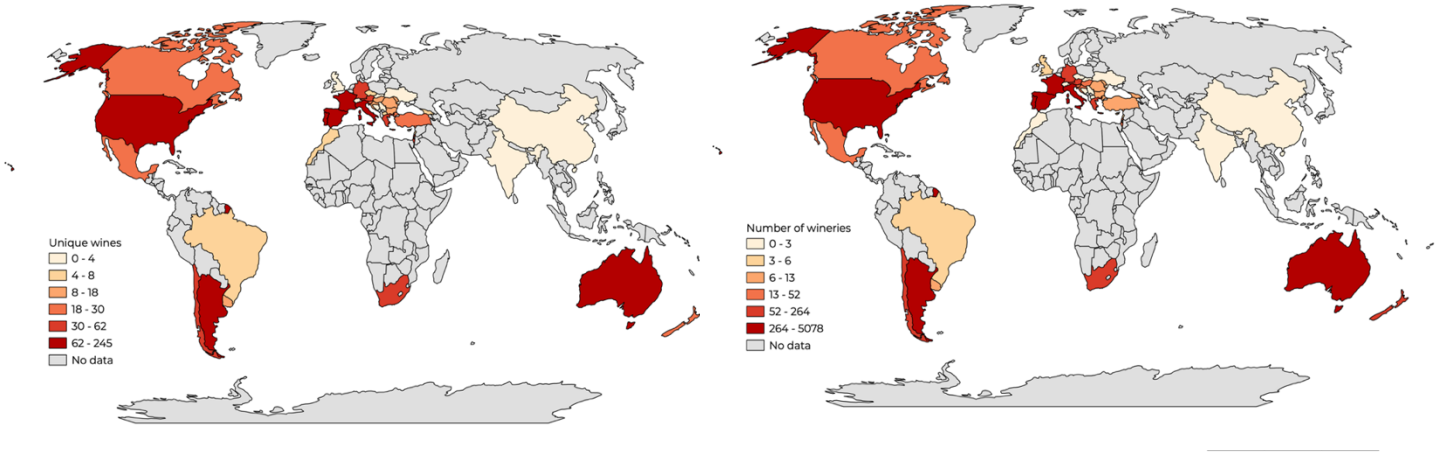

Figure 6. Number of a) unique wines; b) unique vineyards per country of origin

4.1.1 Wine growing regions

In addition to global level analysis, spatial patterns of the high-quality wine regions and districts with the best price-quality ratio were identified in four grapevine regions: Europe, North America, South America and Oceania.

4.1.1.1 Europe

There are many countries in Europe which have various viticultural regions producing high-quality wines. It is clear that these are famous regions, known for high quality of wine making (Fig.8).

In France there is a clear pattern of highly-rated and expensive wines (Fig. 8, 9). On the East of France there is a Champagne region, on the South of the country there two regions, which produce high-

quality wines, they are Provence and Rhône Valley, on the West there is a Bordeaux region (Fig 8 (2), (3), (5)). According to the map (Fig. 8 (1)) in the central part of Portugal there are two regions, which produce highly-rated wines, these are Dão and Douro Valley regions. These are the regions with the highest prices in the country, although the quality and price variance there is high (Fig.9). In Italy there is a Tuscany viticultural region, where the high-quality wine is produced. However, the quality price ratio in Dão and Douro Valley in Portugal is highest, which means that the wines, produced there have high quality with moderate prices (Fig. 10 (a)). In Champagne viticultural region in France and Tuscany in Italy, the ratio is lower, thus the wine prices are high there, such as the quality of wine.

Most of these viticultural regions in Europe, such as Champagne region in France or Tuscany in Italy have high quality and price variation (Fig. 8 (5), 8 (4)). There is the high concentration of the vineyards in these regions (Fig. 7) Although, the variance of quality-price ratio in these regions is low, it is higher in Dão and Douro Valley and Bordeaux regions. One of the reasons of the high variance can be the number of low- and high-quality wines produced, because of the amount vineyards, where can be the well-known premium wine producers and the ones which make lower quality wines.

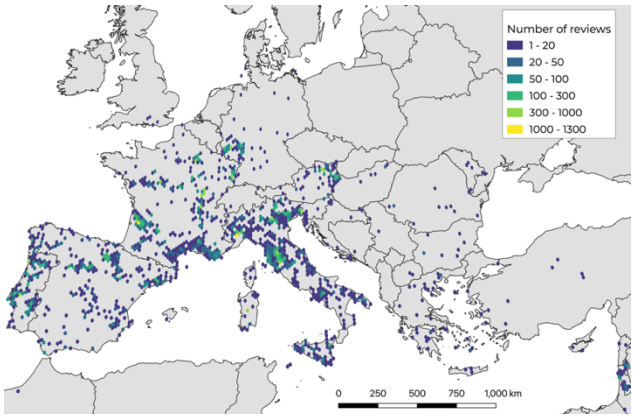

Figure 7. Number of wine reviews in Europe

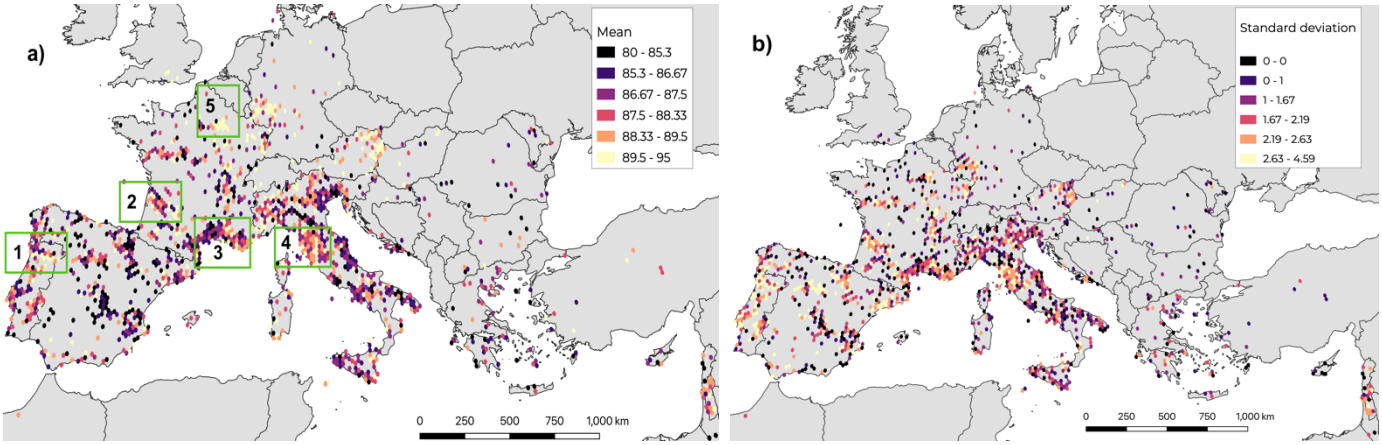

Figure 8. Quality point statistics for a) mean; b) standard deviation values. Regions: 1 – Douro Valley, Dão (Portugal), 2 – Bordeaux (France), 3-Provence, Rhône valley (France) 4- Tuscany (Italy), 5- Champagne (France)

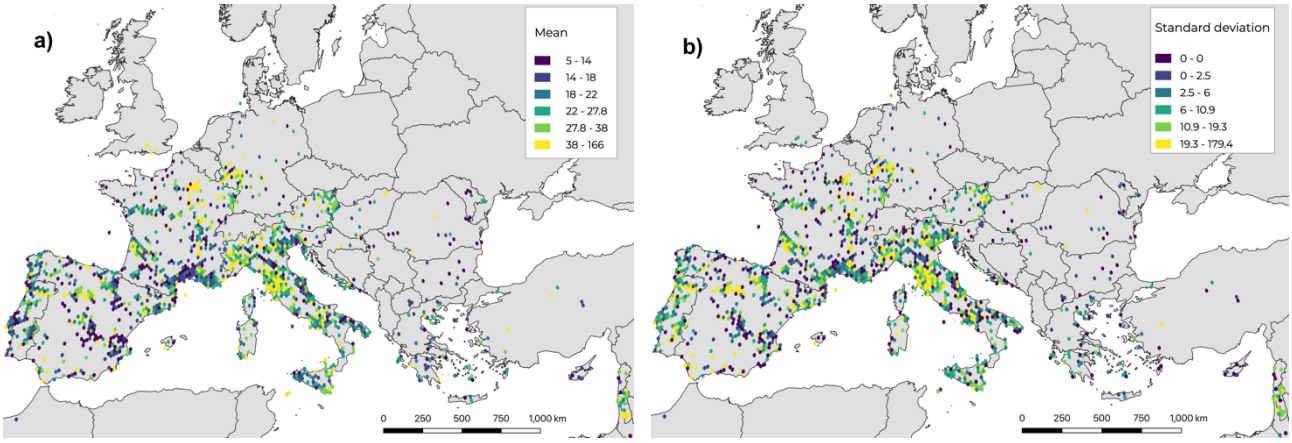

Figure 9. Price point statistics for a) mean; b) standard deviation values

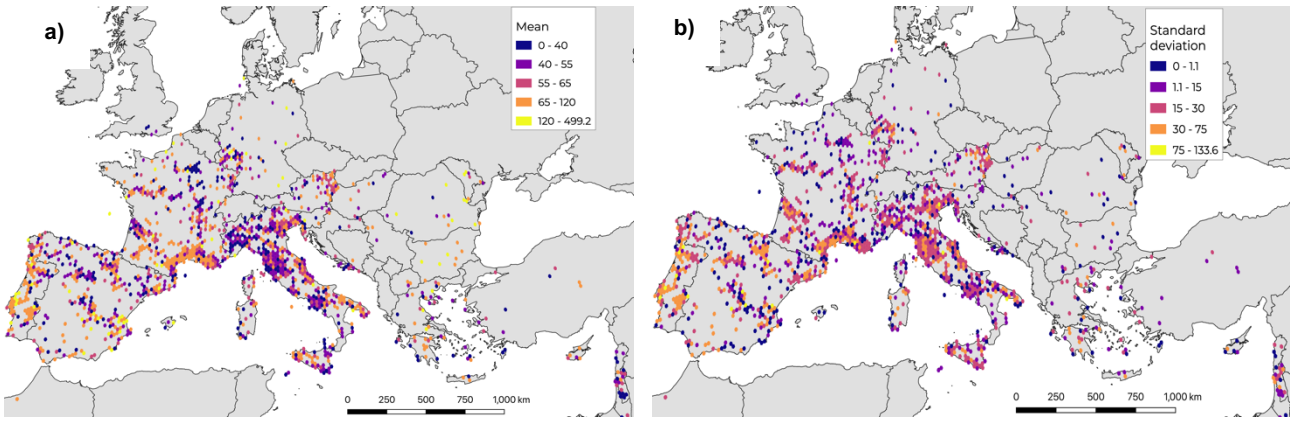

Figure 10. Quality-Price Ratio point statistics for a) mean; b) standard deviation values

4.1.1.2 North America

Most of the wine reviews are made in California state (Fig. 11). The variation of wine quality in this state is the highest, which can be explained by the number of vineyards, producing low- and high-quality wines (Fig. 12). In North America most of highly-rated wines are produced on the West coast of the USA. There are 3 major viticultural areas, which are the state of Washington, Oregon and California, with many sub-regions (Fig. 12).

The most expensive wines on the continent can be found on the western coast of the USA in some sub-areas of California, Oregon and Washington states (Fig. 12). In Washington it is Puget Sound and Columbia Valley (Fig. 12 (1)), in Oregon it is called Snake river Valley and Willamette valley (Fig. 12 (2)) and in California they are mostly locate in the California Central Coast area (Fig. 12 (3)). Sub-regions with high price wines are the districts of Santa Barbara County and San Luis Obispo County (Fig. 13 (1), (2)). Also, San Francisco bay and Santa Clara Valley in the California Northern Coastal area have vineyards, producing highly-rated and expensive wines (Fig. 12, 13 (3)). However, these are the regions with the highest quality-price ratio (Fig. 14). Although, the variance of the price,

quality and their ratio are higher than in other viticultural areas. This also can be explained by the number of vineyards, located there, as there are small vineyards, producing premium wines and others that provide lower quality wines, which are cheaper than luxury ones.

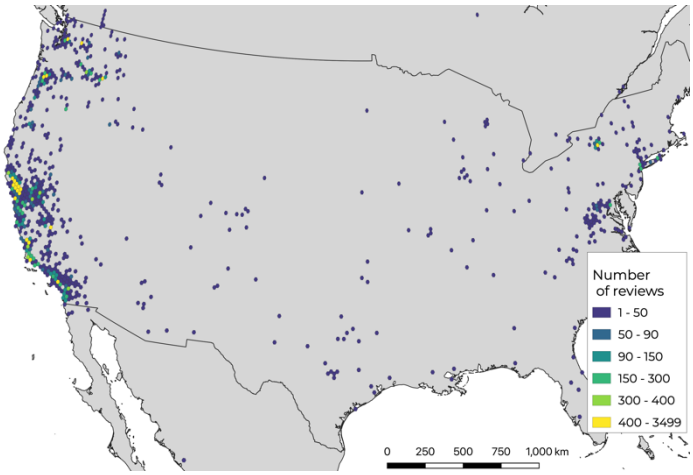

Figure 11. Number of wine reviews in North America

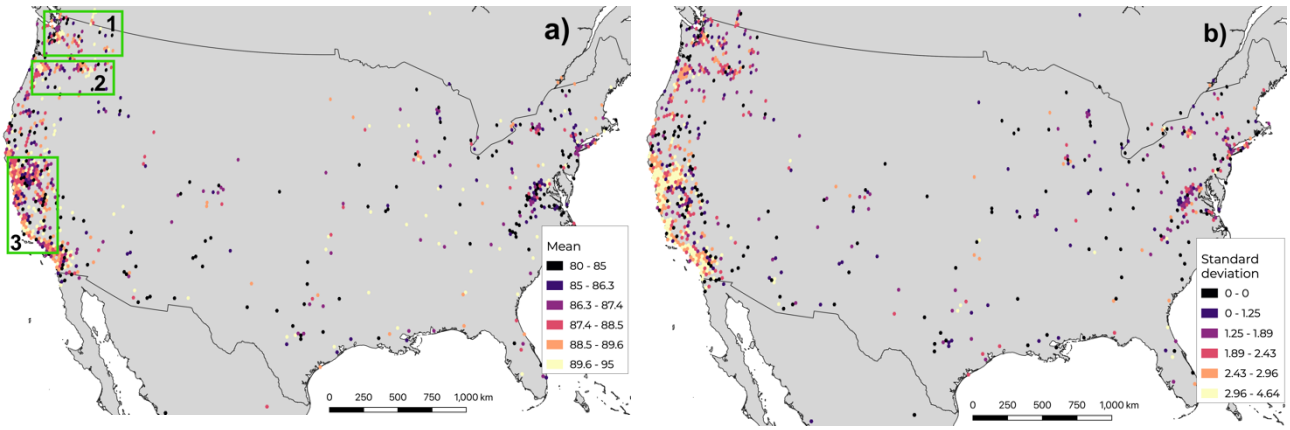

Figure 12. Quality point statistics for a) mean; b) standard deviation values. Regions: 1-Puget Sound, Columbia Valley, 2-Snake river Valley, Willamette Valley, 3- California Central Coast

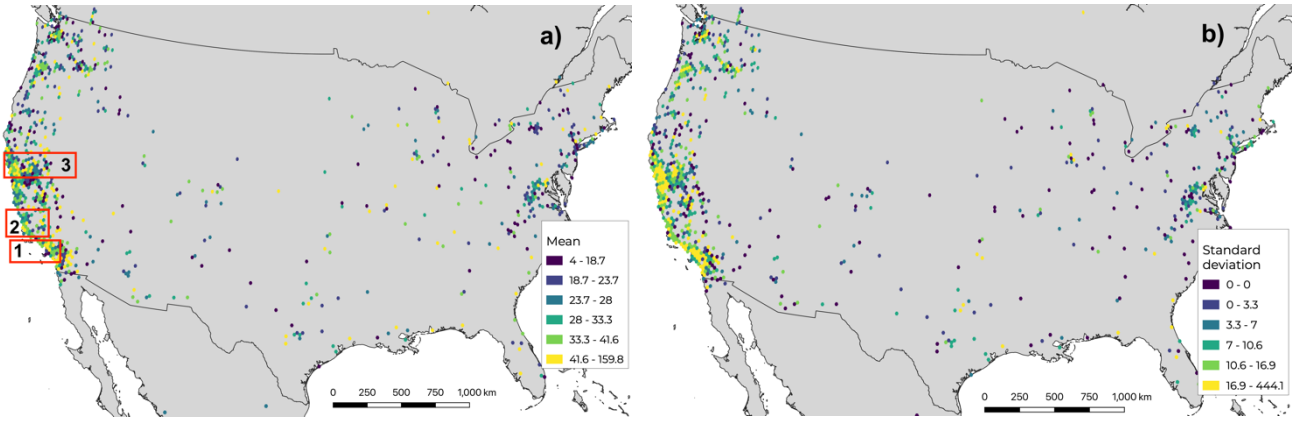

Figure 13. Price point statistics for a) mean; b) standard deviation values. Regions :1-Santa Barbara County, 2-San Luis Obispo, 3- San Francisco bay, Santa Clara Valley

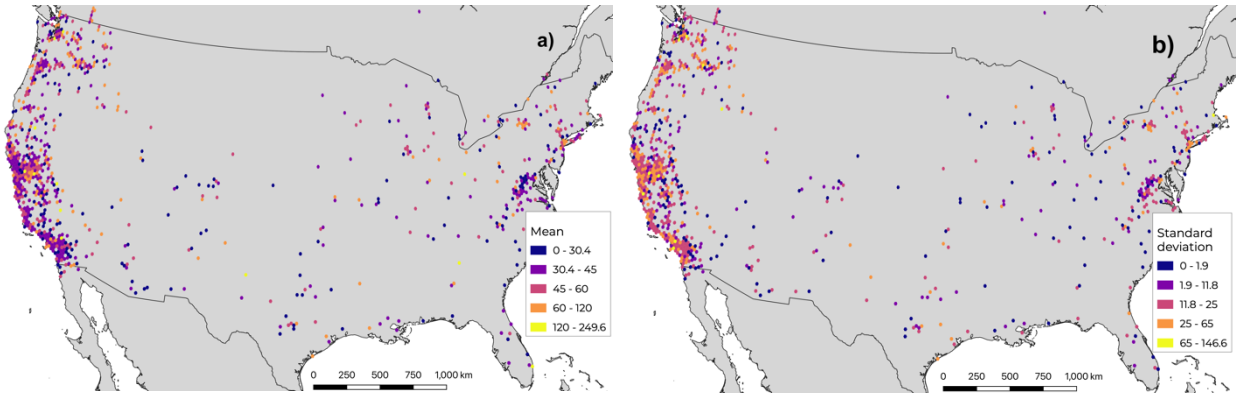

Figure 14. Quality-Price Ratio point statistics for a) mean; b) standard deviation values

4.1.1.3 South America

In Chile viticultural regions are located in the central part of the country. Maule Valley and Central Valley regions are the areas which are producing the most highly-rated wines in the country. Moreover, Maipo Valley on the North of wine producing regions and Malleco Valley on the South are producing higher quality wines than the major part of wine areas in Chile (Fig. 16 (1), (2)).

The largest wine region in Argentina is Mendoza. There the most highly-rated wines in the country come from (Fig. 16 (3)). However, there are few more regions such as Salta on the North of the country and Rio Negro, which is located on the upper valley of the river Rio Negro, where the high-quality wines come from (Fig. 16 (4)). The most expensive wines can be found in the viticultural region Rio Negro and Maipo Valley, where the best ratio for quality-price is (Fig.18). Prices on the rest of the continent are lower (Fig. 17).

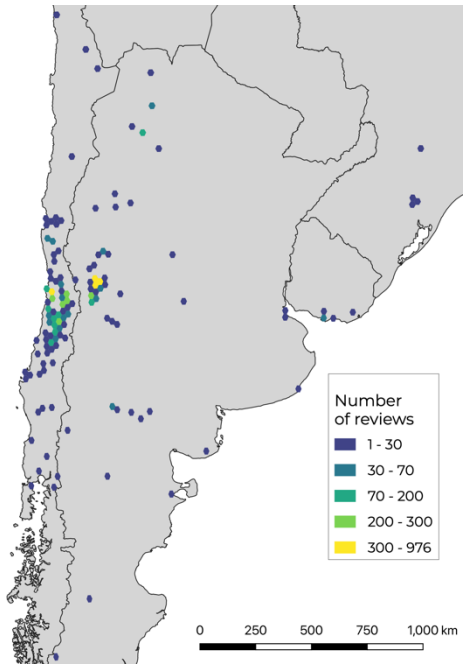

Figure 15. Number of wine reviews in South America

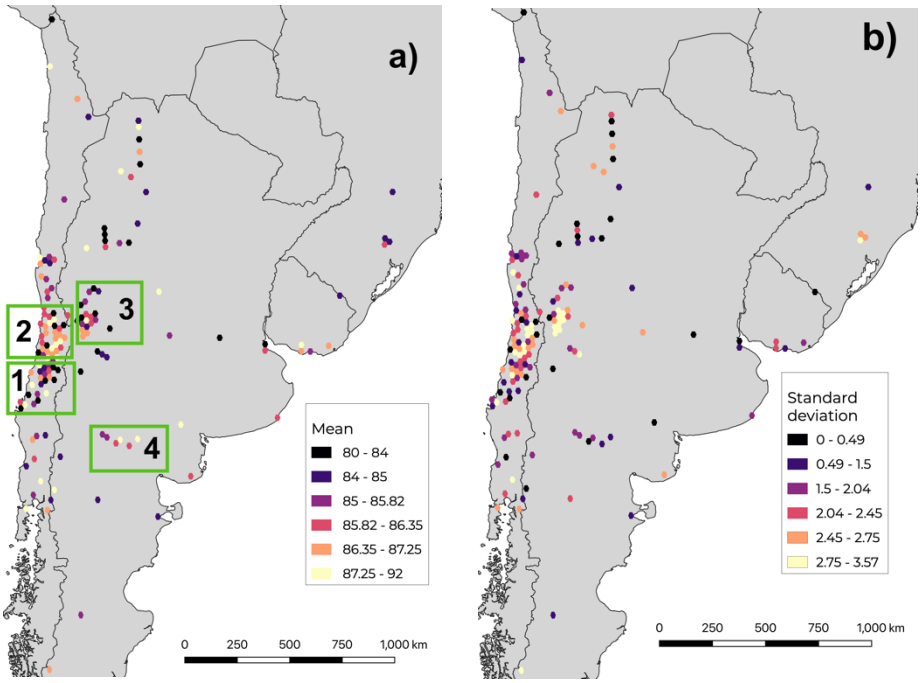

Figure 16. Quality point statistics for a) mean; b) standard deviation values. Regions: 1-Maule Valley, 2-Maipo Valley, 3-Mendoza, 4-Rio Negro

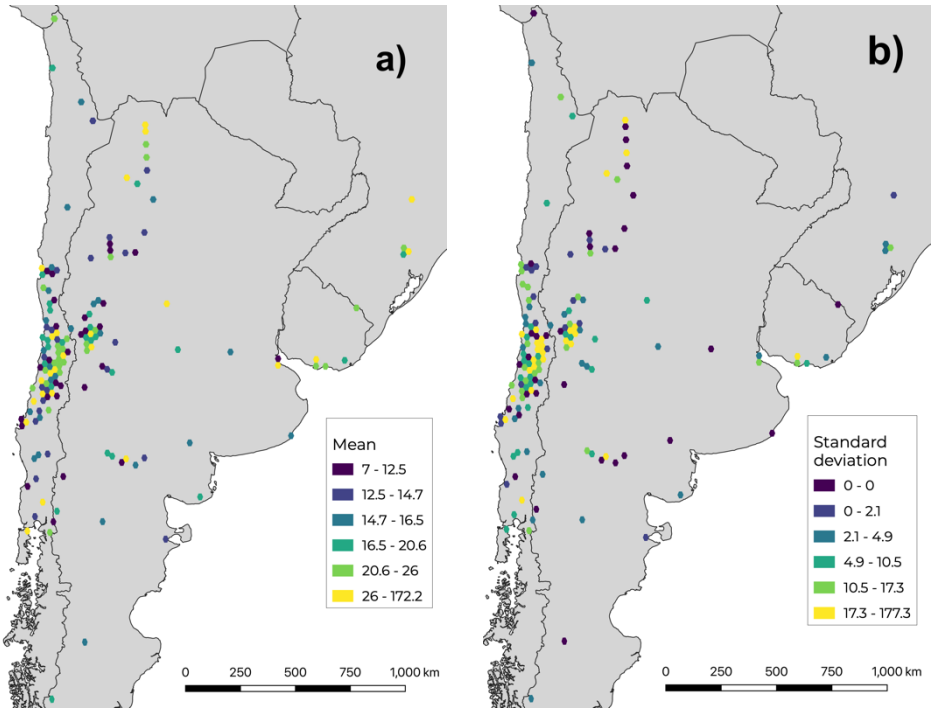

Figure 17. Price point statistics for a) mean; b) median; c) standard deviation values

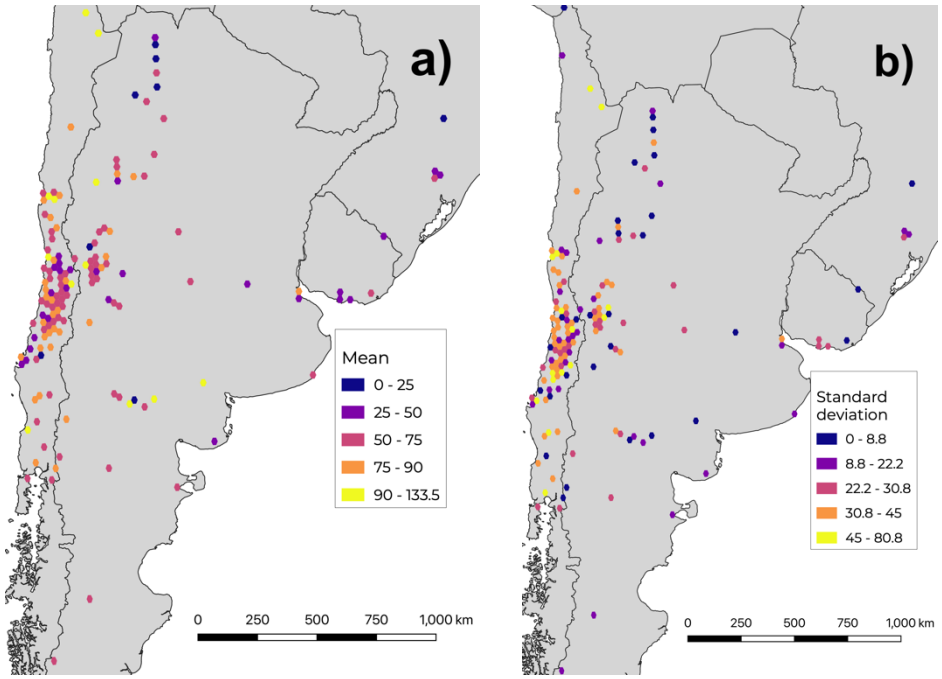

Figure 18. Quality-Price Ratio point statistics for a) mean; b) standard deviation values

4.1.1.4 Oceania

There is a clear pattern of the viticultural regions, producing highly rated, expensive wines, which also have high price-quality ratio. These are the vineyards, located on Southern the coastal areas in Australia, which are Great Southern, Adelaide and Melbourne (Fig. 20 (1), (2), (3)). Viticultural areas located on Tasmania island are also shown as the territories with high-quality wine production (Fig. 20 (4)). In New Zealand there is a small amount of wine producing regions, most of them located on the coastal areas. The areas with highest quality and prices are the Central Otago and Marlborough areas (Fig. 20 (5), (6), Fig.21).

Most of these viticultural regions in Oceania have high variance of all three variables presented, when the concentration of the vineyards is also high (Fig. 20, 21, 22). However, the Marlborough region in New Zealand has a slightly lower quality-price ratio, with highly-rated wines and lower prices than in other presented regions. One of the reasons explaining this pattern can be the lower number of reviewed vineyards in Oceania than in Europe or USA. So, there can be presented bigger proportion of reviews for highly rated wines. On the other hand, there are more vineyards, located in the Marlborough viticultural are can simply produce high quality wines with moderate prices.

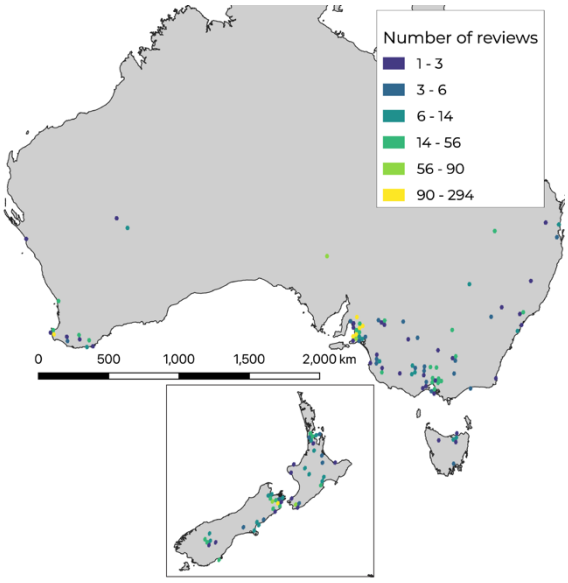

Figure 19. Number of wine reviews in Oceania

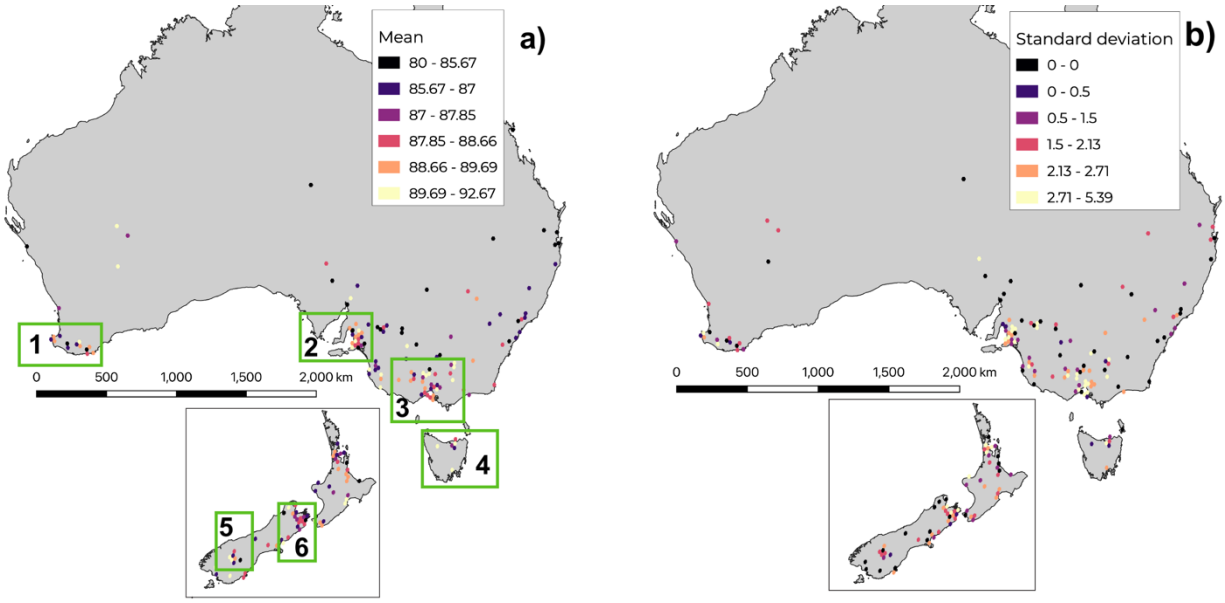

Figure 20. Quality point statistics for a) mean; b) standard deviation values. Regions: 1- Great Southern, 2- Adelaide, 3- Melbourne, 4-Tasmania, 5- Central Otago, 5-Marlborough

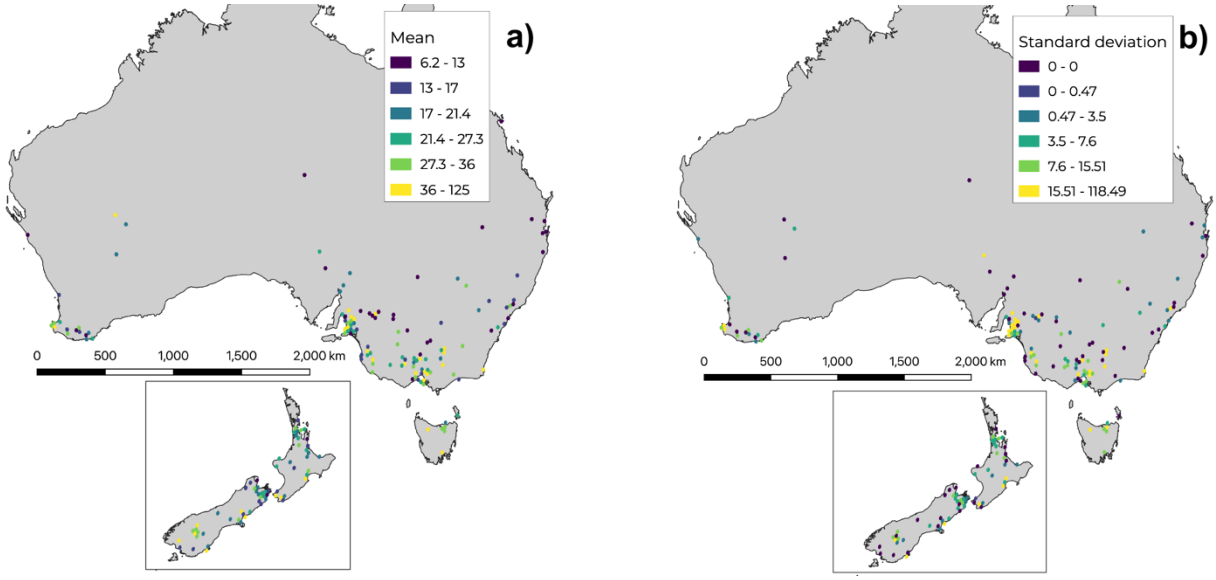

Figure 21. Price point statistics for a) mean; b) median; c) standard deviation values

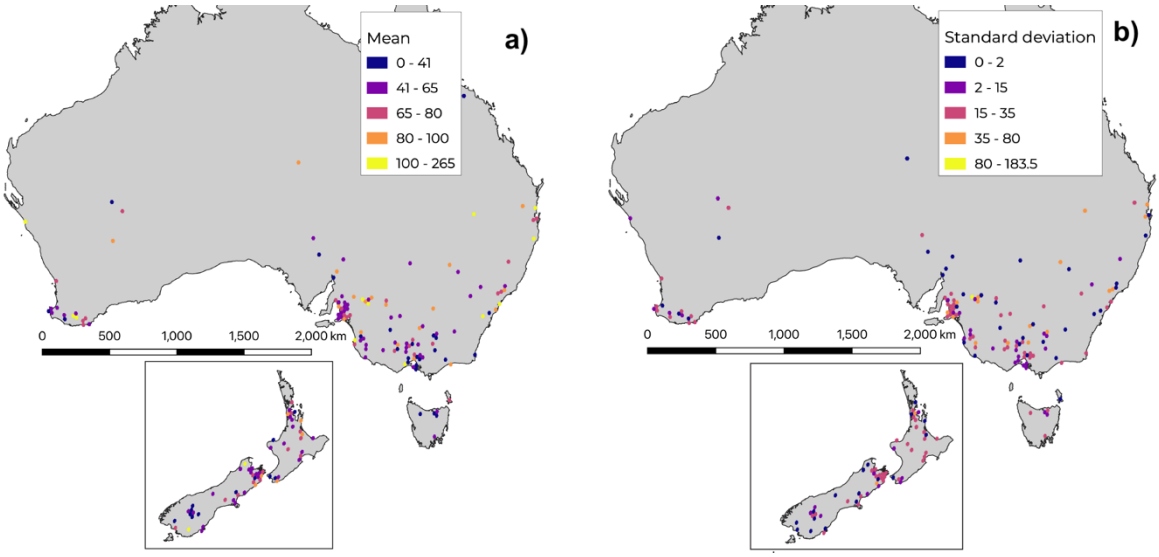

Figure 22. Quality-Price Ratio point statistics for a) mean; b) standard deviation values

4.1.1.5 Spain

Spain is one of the countries producing high-quality wines. The main wine producing regions, where highly-rated wines come from are La Rioja, Catalonia, Castille and Leon, Galicia (Fig. 23, 24). All these regions are located in valleys near the mountains. In some of these regions the variance of quality and price is high, such as the number of the wine reviews.

La Rioja region located in the North of the country has the biggest number of the reviews, which is 1/5 of the whole number for this country. This region produces numerous highly-rated wines, but not the most expensive. The cheapest wine from this region will cost 6$ and the most expensive 350. Also, the points for the wine quality are not the highest in the country. “Bodegas Roda 2009 Cirsion” has 97 quality points and can cost up to 200$ per bottle, when “J. Garcia Carrion 2009 Antaño” from the same region will cost around 6$, but the quality of this wine is lower and consists of 84 points.

Catalonia is a small wine production region located on the East coast of the country in the North. It has many subregions and Penedes subregion has the biggest number of the reviews for Catalonia. However, the biggest amount of highly-rated wines are coming from Priorat and Montsant areas on the South of the region and Pla de Bages in the middle. Marco Abella vineyard in Priorat region produces the most prestigious wine in Spain. “Marco Abella 2012 El Perer Carignan”, according to the dataset, costs 770$ and has 96 quality points out of 100. In contrary, Paul Cheneau vineyard located in the same region, produces “Paul Cheneau NV Blanc de Blancs Brut Chardonnay”, which costs only 6$ per 750ml bottle.

Castille and Leon region consists of several sub regions and has less amount of wine reviews, but still the wines, which produced in this area are highly-rated. The best wines are coming from Ribera del

Duero, Cigales, Ruecla and Toro subregions. The wine, which has the highest quality rating is produced in Ribera del Duero "Emilio Moro 2009 Clon de la Familia" and it has 98 quality points out of 100 and costs 400$, which is the highest in the country. However, it is not the most expensive wine in Castille and Leon. Wine "García Figuero 2012 Tinus" costs 600$ and it's a highly-rated wine with 95 quality points. The mean wine price in some parts of Castille and Leon region is 122 $.

Galicia is a small region located on the West coast of the country in the North. It doesn't have a big number of vineyards there, but has a high-quality wine production. The highest quality review is 94 for the wine "Telmo Rodríguez 2010 M2 de Matallana". Compared to other regions, the price of 45$ is not high for such highly-rated wine. However, the most expensive wine in Galicia is 147$ for also highly-rated wine. Although, the wine prices and quality are high in these regions, the quality-price ratio shows low values (Fig. 26).

Valencia region shows stable production lower quality wines and the variance of quality and price is low. However, the quality-price ratio is higher than in bigger viticultural regions. This means that the vineyards produce relatively high-quality wines with lower prices. Also, the amount of wine reviews and vineyards is significantly lower than in the main wine-producing regions of this country and consists of 218 reviews. This region also contains few sub-regions, where the main is Alicante and the most expensive and highly-rated wines are produced in it. Bodegas Gutiérrez de la Vega vineyard, located in this subregion, produces "Bodegas Gutiérrez de la Vega 1999 Casta Diva Fondillón Sweet Monastrell" wine, which costs 88$ per 750ml bottle and has 97 quality rating. Utiel-Reuena subregion produces lower quality wines, which are respectively cheaper. The highest price for the "Dominio de la Vega NV Artemayor Brut Nature Sparkling", wine is 38$, when the cheapest is "Viña Decana 2010 Crianza Tempranillo" and costs about 5$.

In other regions, such as Extremadura or Murcia regions wine production is lower and there are not so many vineyards presented. The wines, produced in these areas has lower quality and cost less than in regions, containing vineyards with high reputation and production of premium wines.

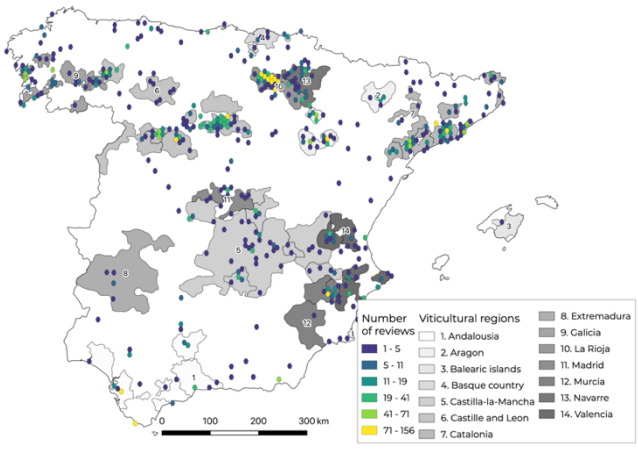

Figure 23. Number of wine reviews in Spain

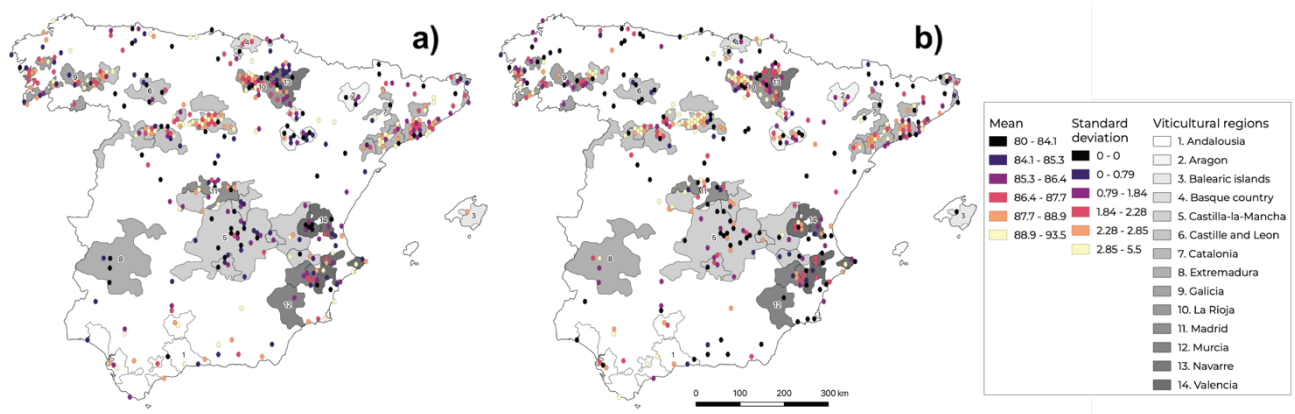

Figure 24. Quality point statistics for a) mean; b) standard deviation values

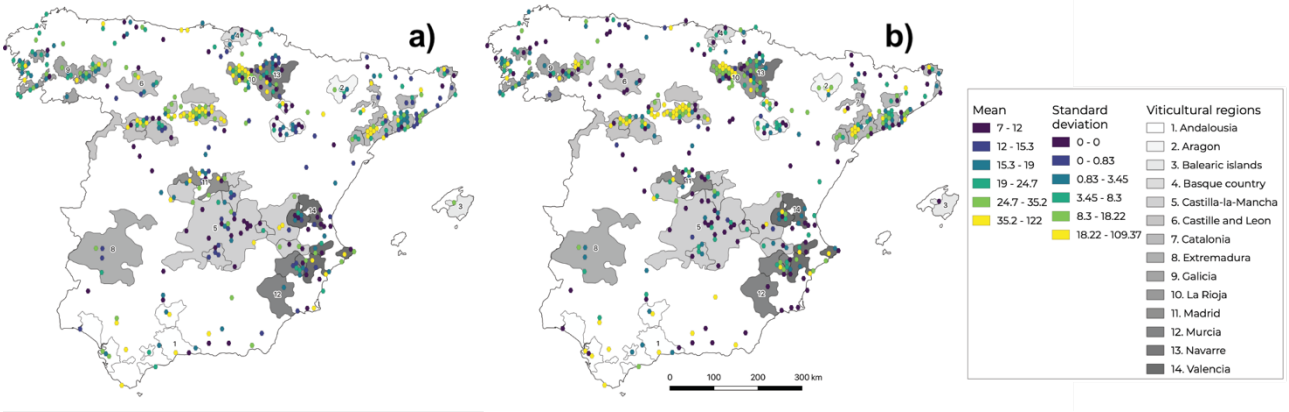

Figure 25. Price point statistics for a) mean; b) standard deviation values

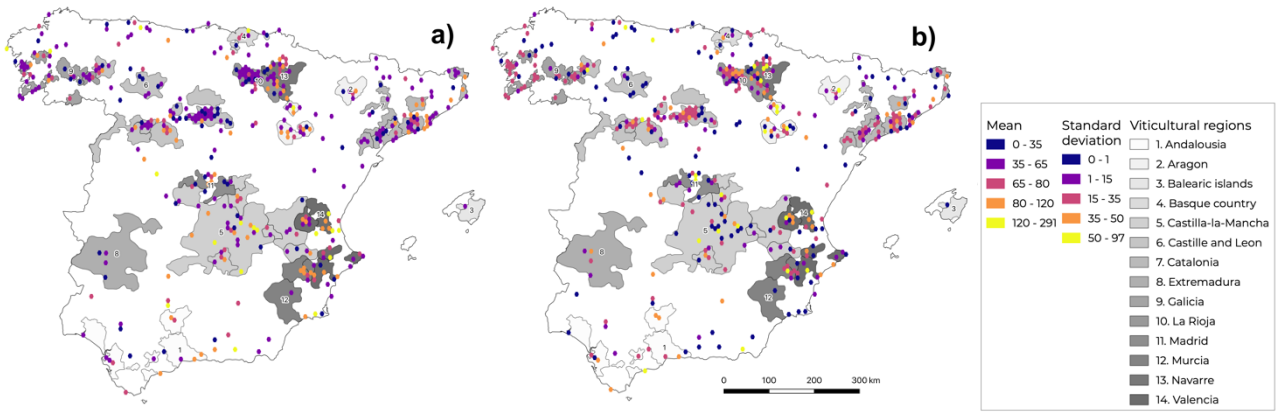

Figure 26. Quality-Price Ratio point statistics for a) mean; b) standard deviation values

4.1.1.6 Wine prices

High variance in wine prices and quality can be explained not only from the number of vineyards in that area. Wine dataset was checked and it was found out that about 1% or less of all the vineyards produce small amount of luxurious wines and very cheap wines (Table 4). Most of these vineyards have price variation of 100$, but some are showing the result of 500 - 600$ or even 2000$. For example, “Adega de Cantanhede” in Portugal has a variance of 89$, when “Domatine du Comte

Liger-Belair" in France has a variance of 2200$. Some of the vineyards produce only premium wines, which can be explained in expensive production. For example, grapes can be hand-harvested and the kind of grape can be difficult to find and grow. Also, the wine can be produced only in specific region, as "Douro Valley" in Portugal or "Bordeaux" in France. Usually these vineyards have small production, which is not possible for production and export cheap wines (Wine Folly, 2019). Also, premium wines are being aged in oak barrels. Oak adds wine a taste, such as vanilla, clove and nutmeg for red wine or raisin, dried fruit and brown sugar taste for white wine (Wine Folly, 2020). It is expensive to store wine in oak barrels. French barrels are the best ones and cost twice more than American oak barrels and the production of them is expensive, as only 2 barrels can be made out of 80 years old tree.

Table 4. Variation of wine prices

Vineyard	Min price, $	Max price, $
Adega de Cantanhede	9	98
Adelsheim	19	125
Amici	15	125
Banfi	130	130
Achaval-Ferrer	25	150
Agricola Querciabella	17	150
Argiano	25	165
Abadia Retuerta	17	199
Alex Gambal	23	200
Avignonesi	13	237
Alpha Omega	**34**	**300**
Baron Knyphausen	**15**	**510**
Albert Bichot	**10**	**530**
Armand de Brignac	300	675
Kopke	**12**	**980**
Chaeau La Mission Haut-Brion	**49**	**1000**
W. & J. Graham's	**22**	**1000**
Domaine du Comte Liger-Belair	**300**	**2500**

4.2 Relationship between wine quality and price

It is shown that the minimum price for the bottle of wine is 4$ and the most expensive wine costs 2 500$ according to this dataset. Although, the range of the price data is wide and the 3rd quartile of it, which is 75% of the data is at 44$ per bottle (Table 5).

Table 5. Summary of the wine price data

Min.	1st Qu.	Median	Mean	3rd Qu.	Max
4.00	17.00	25.00	35.96	44.00	2500.00

Graphical representation of the distribution of prices according to the wine type illustrates that Rosé wine is the cheapest and Red and Red/White/ Rosé wine types are the most expensive in the dataset (Fig. 27). As the price range is wide, the outliers were deleted, to better visualize the data.

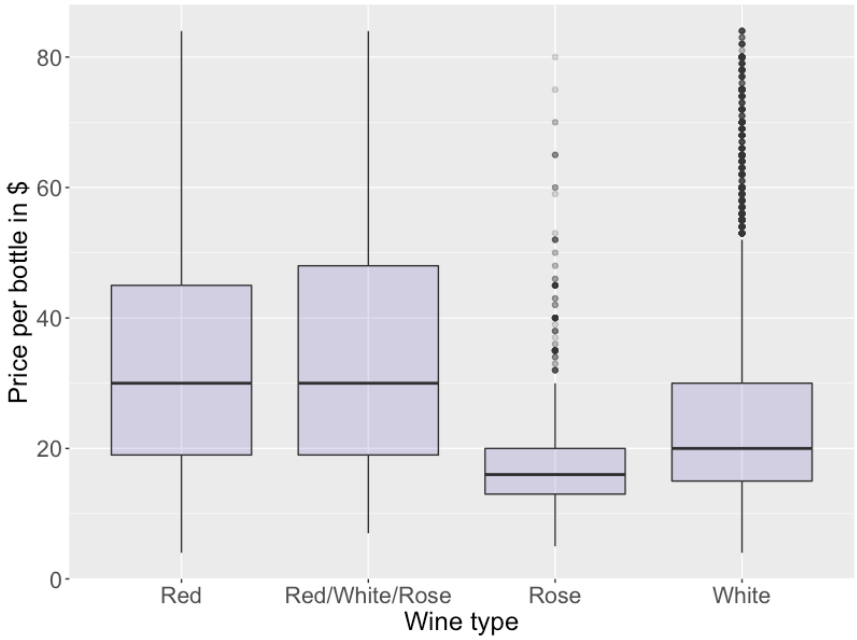

Figure 27. Boxplots for wine price according to wine type.

The correlation analysis by 4 price groups of wine (cheap, mid-priced, expensive, all data) showed that the strongest relationship between price and quality points was in fourth group (Fig. 28), where the correlation test was performed for the whole dataset. In all cases the correlation was positive indicating that the wines with higher review score cost more.

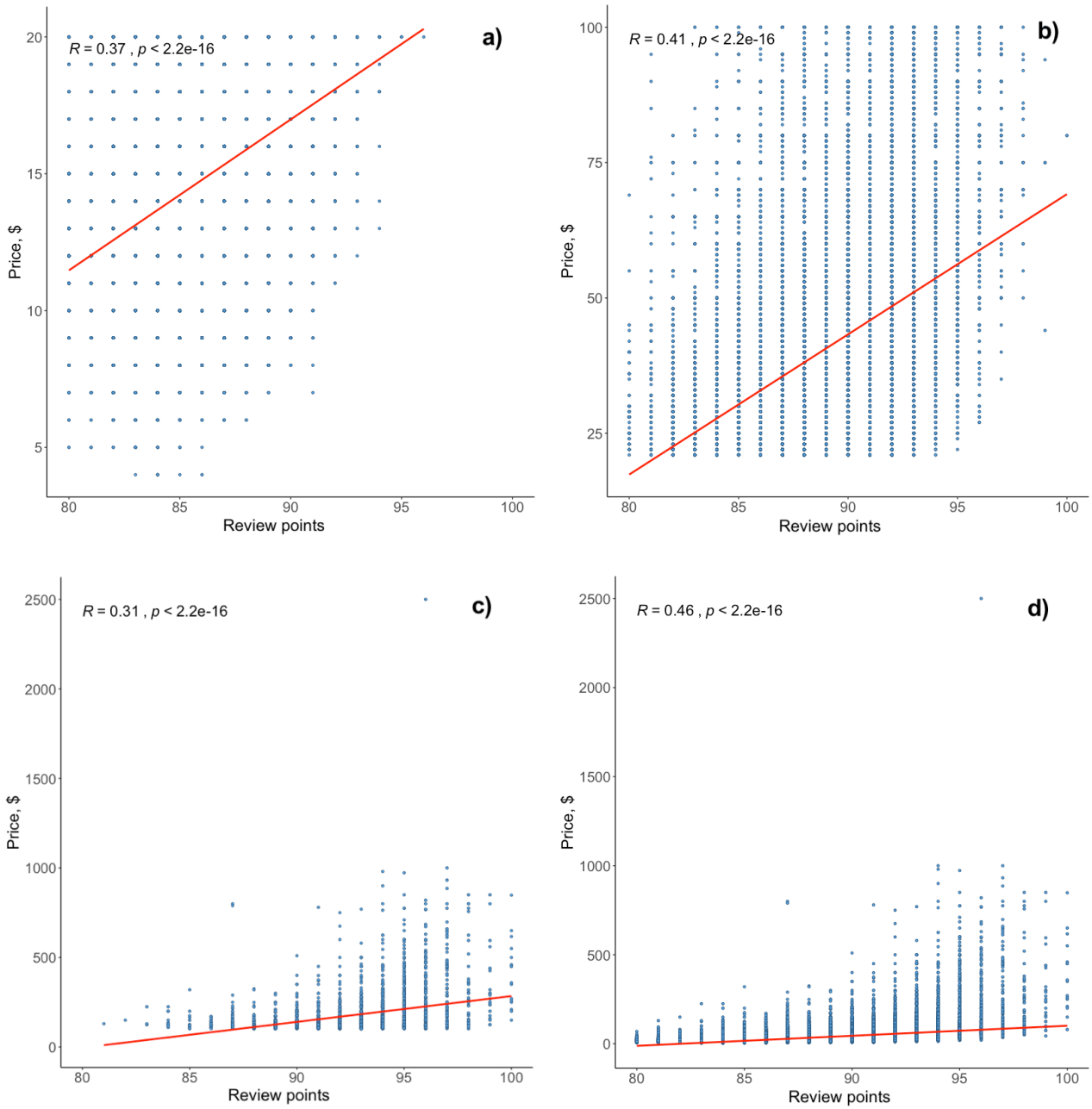

Figure 28. Relationship between wine quality points and wine price for the a) cheap wines; b) mid-priced wines; c) expensive wines; and d) all wines

4.3 Relationship between wine quality, price and climatic and soil variables

4.3.1 Correlation analysis

The results of the correlation analysis showed that there is either no correlation or some weak negative and positive linear relationships between wine quality and the climatic variables (Table 6; Figure 30). The correlation results are statistically significant, as p-value is less than level of significance (0.05). Previous studies have shown that the climate is one of the main factors influencing wine quality. For example, high temperatures increase the level of sugar in the berry, but the effect on anthocyanins,

which are the main elements that compose the wine color is negative (Jones et al., 2005). However, current study did not confirm this. The results of the correlation tests for soil variables showed that there is almost no correlation between variables (Table 6), Only sand content and wine quality showed weak negative relationship. The higher the sand content, the lower the wine quality.

Table 6. Results of the correlation analysis between wine quality and the climatic and soil variables

Variable	Correlation coefficient	P-value
Annual precipitation	0.054	<0.001
Summer precipitation in NH	-0.014	0.031
Winter precipitation in NH	0.044	<0.001
Summer precipitation in SH	0.042	<0.001
Winter precipitation in SH	0.052	<0.001
Annual mean t˚	-0.092	<0.001
Min t˚of the coldest month	-0.012	<0.001
Max t˚ of the warmest month	-0.103	<0.001
Average summer t˚ in NH	-0.125	<0.001
Average summer t˚ in SH	-0.114	<0.001
Annual solar radiation	-0.112	<0.001
Clay content	0.007	<0.001
Sand content	-0.104	<0.001
Total Nitrogen	0.026	<0.001
Soil pH	-0.039	<0.001

However, the correlation analysis and plotting the relationships revealed that there are non-linear relationships between wine prices and other variables (Fig. 30).

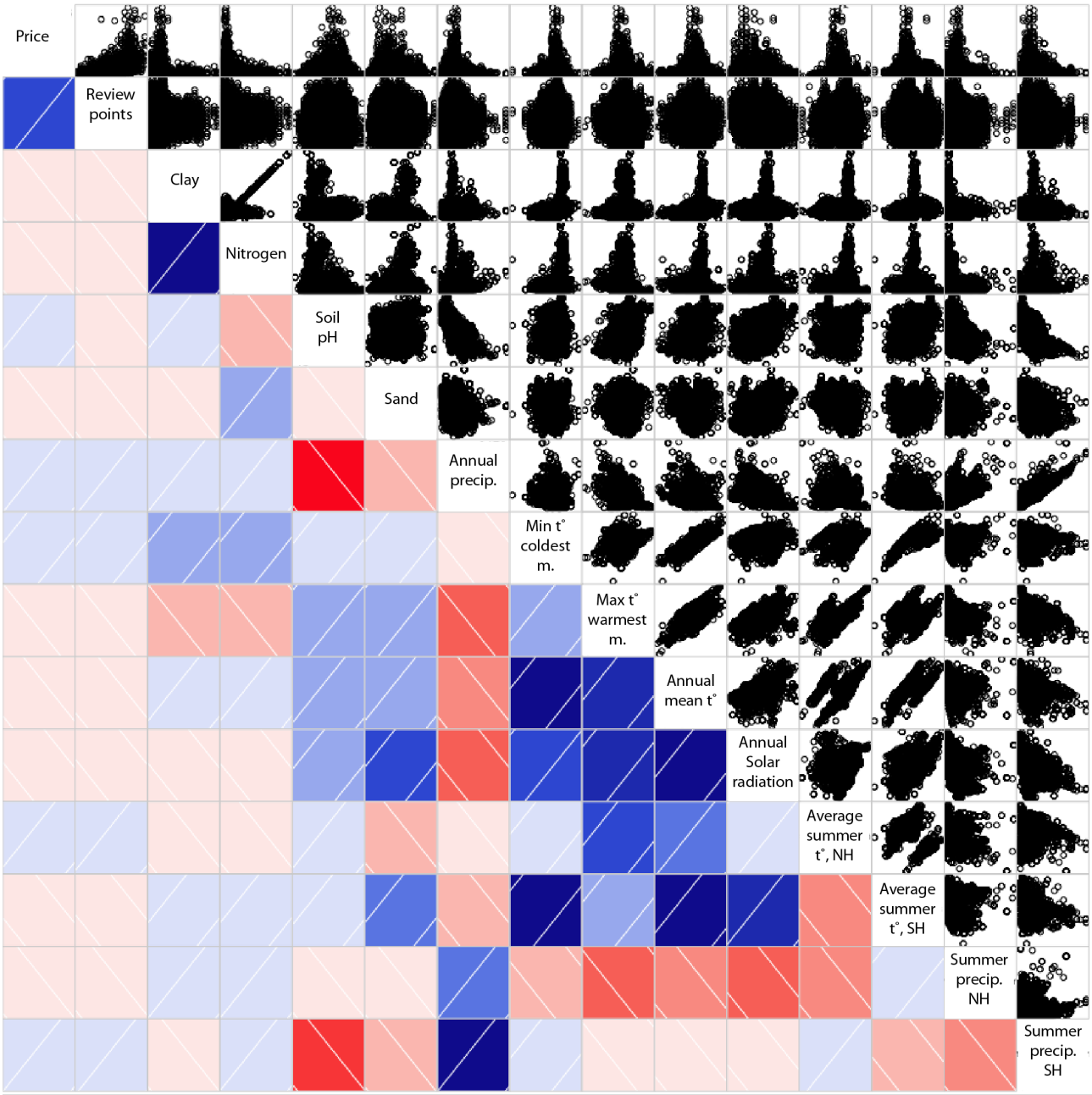

Figure 30. Correlation matrix for wine quality and price, and soil and climatic variables. Blue color – positive correlation, red color – negative correlation. Intensity of the color – correlation strength.

There is a non-linear relationship between wine prices and minimum temperature of the coldest month, maximum temperature of the warmest month, annual mean temperature and average summer temperatures in both hemispheres (Fig. 31). The wine price decreases with too low or too high temperatures, when the most expensive wines are located in the temperature range from 9~10 to 17~18 ˚C (Fig 31 (a)). Jones et al. (2005) pointed out similarly that the average suitable temperature for production of high-quality sweet wines is about 16-18 ˚C. Orduña (2010) describes that cool

temperatures are appropriate for the aroma development of white wines, when too high temperatures can decrease its intensity. However, the relationship between price and annual mean temperature is statistically insignificant as the p-value is higher than 0.05 (Fig.31 (a)). Also, the suitable summer temperature for the high priced wines in both Northern and Southern Hemispheres is in the range from 15-25 ˚C. (Fig. 31 (e), (d)). The extreme temperatures also affect the wine prices. For example, temperatures lower than -10 ˚C or higher than 32 ˚C decrease the wine price (Fig 31 (b), (c)). As it was underlined in literature, temperatures over 30 ˚C and higher has an effect of reduction the size of the berry, which can have an impact on the amount of sugar (Orduña, 2010; Zsófi et al., 2011).

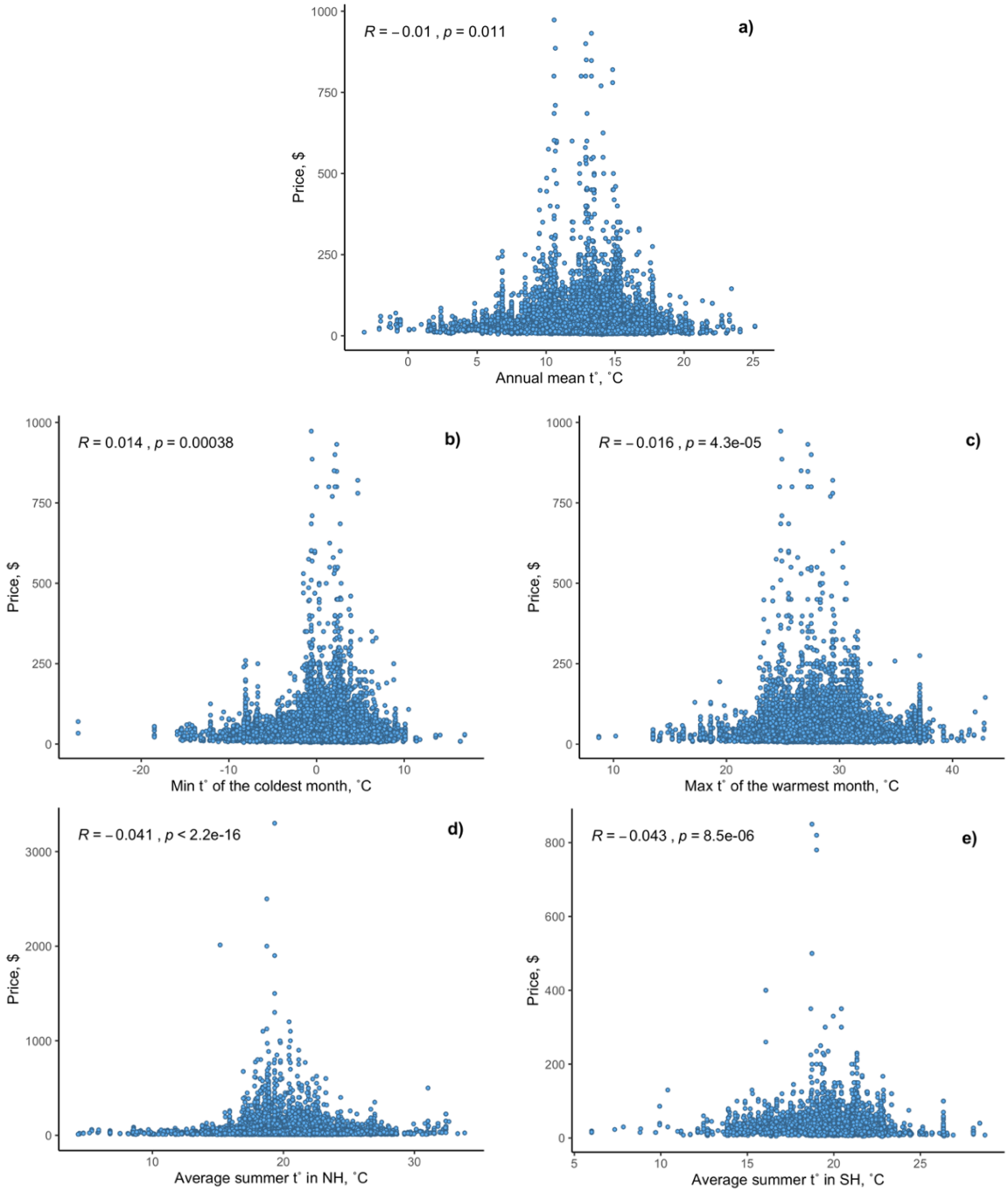

Figure 31. Relationship between wine price and a) Annual mean t˚, b) Min t˚ of the coldest month, c) Max t˚ of the warmest month, d) Average summer t˚ in NH, e) Average summer t˚ in SH

There is a non-linear relationship between wine prices and precipitation. The price decreases with the higher amount of precipitation. The most expensive wines are produced in a range of 100-1000 mm and the price start to decrease after 1000 mm. Areas with 0-100 mm and 2000 – 3000 mm precipitation do not have expensive wines (Fig. 32 (a)). Overly wet conditions throughout the growing season are not good for wine production because wet conditions are important during plant creation, whereas dry conditions are needed for the berry ripening in summer (Merloni et al., 2018). In both Southern and Northern hemispheres the relationship between wine price and precipitation in summer is also non-linear (Fig. 32 (b), (c)). The highest wine prices are located in the range from 0 to 300 mm and from 400 mm there are less expensive wines. It was described in the previous studies, that the good conditions for the grape formation are dry and warm, which are important for the amount of acid and sugar in berries and the ideal precipitation during grape formation is 63 mm for red wines and 48 mm for white wines (Baciocco et al., 2014).

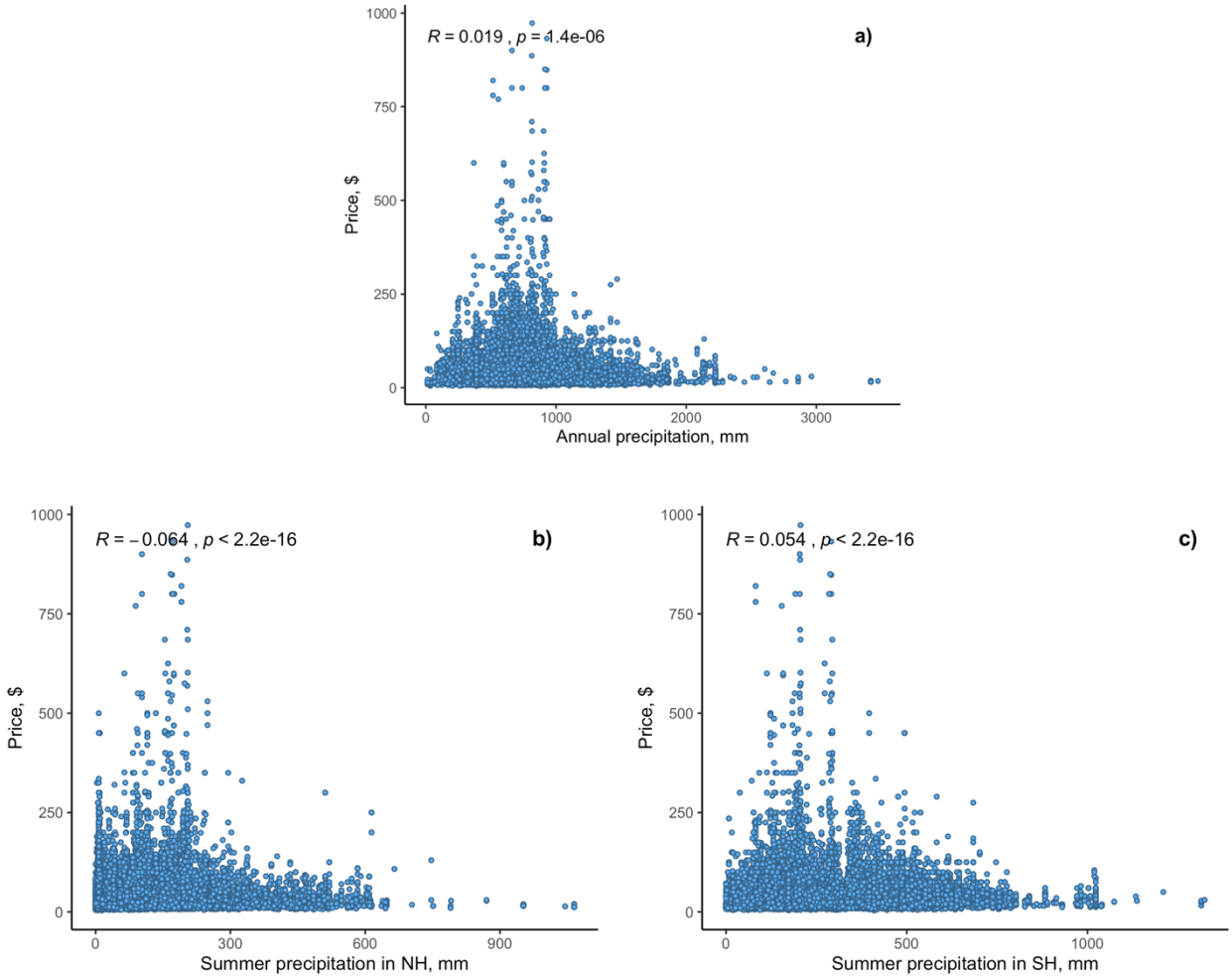

Figure 32. Relationship between wine price and a) Annual precipitation, b) Summer precipitation in NH, c) Summer precipitation in SH

Relationship between wine price and Clay and Nitrogen content in soil is non-linear and presented as a decay (Fig. 33 (a), (b)). Low Nitrogen and Clay compounds are suitable for higher priced wines,

when with the increase of these chemical elements, the wine price decreases significantly. The most expensive wines are distributed in the range of Clay content in soil from 200-500 ‰ and Nitrogen content 100-300 ‰. According to Fayolle et al. (2019), the lower Nitrogen in soil the higher the quality of red wine. Moreover, Spangenberg et al. (2018) points out that the Nitrogen content is lower in dry soil, which confirms that the dry warm summer is an ideal condition for high- quality wines production. Clay composition in soil affects the soil water availability status, which means that the lower the clay content, the lower the water status (Jasse et al., 2021). So, the right amount of Clay particles in soil can create good conditions for producing high-quality wines.

Sand content and soil pH have a non-linear relationship with wine prices (Fig. 33 (c), (e)). Too low or too high values decrease the wine prices. The most expensive wines are presented in a sand content range from 200-550 ‰ and soil pH 60-80. Level of pH in soil affects the wine acidity, so the lower pH, the higher total acid level in the grapes (Cravero, 2019). With high pH level there is a decrease in anthocyanins composition, which creates the red wine color (Forino et al., 2020). With a very low pH level, the amount of anthocyanins is high and the color of the wine is rich red, but the acidity level is also high.

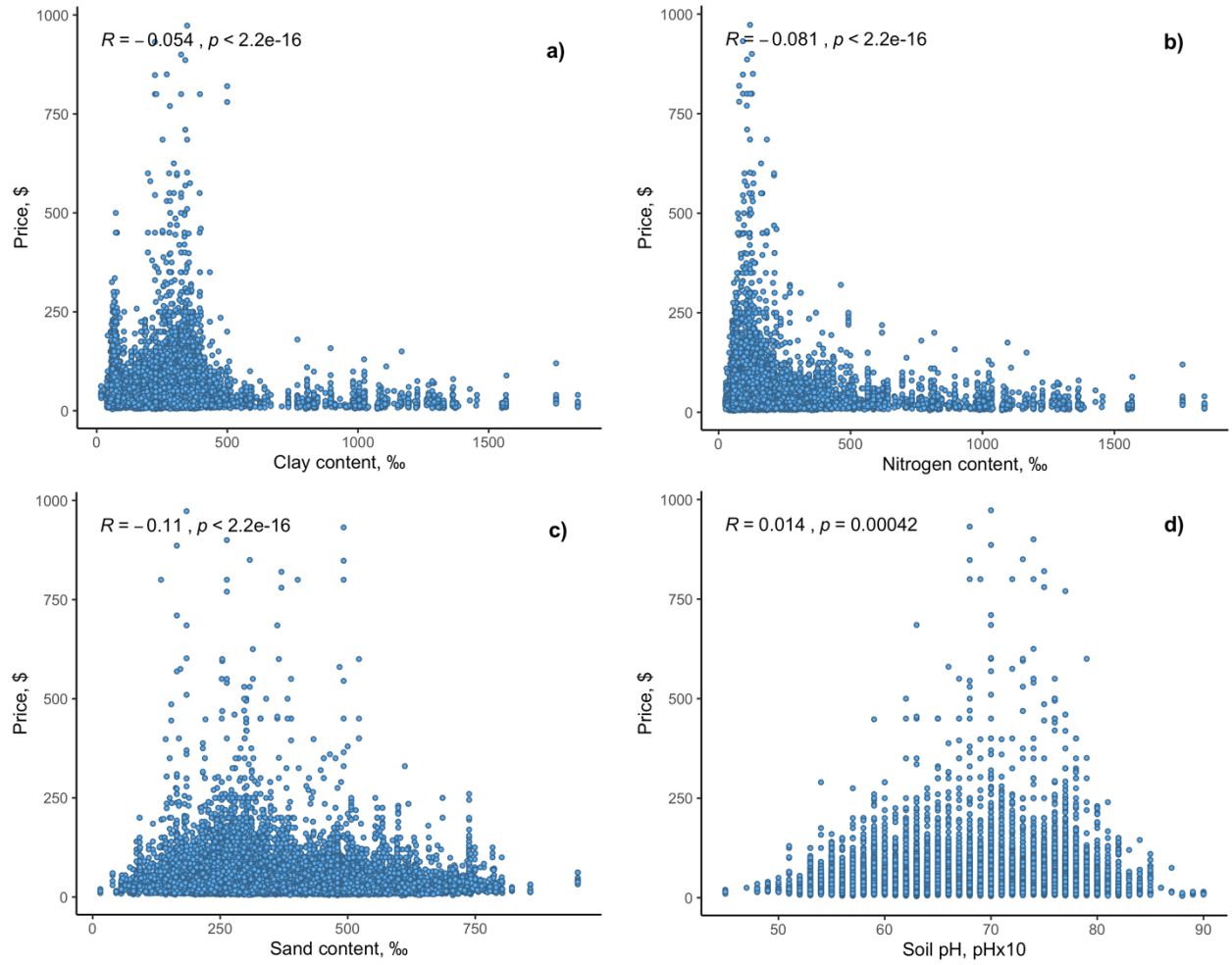

Figure 33. Relationship between wine price and a) Clay content, b) Nitrogen content, c) Sand content, e) Soil pH

5 Conclusions

The main goal of this research was to evaluate the spatial patterns of wine prices and quality based on the wine reviews, and identify whether there is a relationship between wine quality/price and climatic and soil variables. As it was underlined in the literature, these are the main factors affecting wine production. In this research it was shown that wine quality is correlated with such climatic conditions as the annual mean temperature, minimum and maximum temperatures and solar radiation, when wine prices have definite non-linear relationships with all soil and climatic variables.

As it was indicated in previous studies, soil conditions also play a significant role in grape growing and wine production (Abbal et al., 2019). However, as a result of correlation analysis, the relationship between wine quality and such soil variables as Clay content, Nitrogen content, Sand content and soil pH is quite low. However, there is a non-linear relationship between wine prices and soil conditions. The amount of Nitrogen in soil affects the wine color, so the lower number of this chemical element is in soil, the higher the quality of the red wine (Fayolle et al., 2019a). Also, the red wine color depends on the soil pH level, and with too low or too high pH, the quality of wine will decrease, as the level of pH affect the amount of anthocyanins, which creates the wine color (Forino et al., 2020). The clay and sand compositions in soil have impact on the water content, which has an effect on the plant and berry formation and ripening (Jasse et al., 2021). High amount of clay particles in soil can hold high amount of water, which can be crucial for the grape formation during summer, as the high-quality wines are produced in a climate with warm and dry summers (Jones et al., 2005). When interpreting the results of the analysis for the soil variables, the limitations of the data must be considered. As it was indicated in the source of the soil data, which is SoilGrids, the data presented there is not the real samples, collected all over the world, but is a modelled data, which was produced using machine-learning methods. The relationship between Clay and Nitrogen is shown as almost perfect and creates a straight line, which cannot be performed in real world.

Various studies have described that there is a strong relationship between wine production and soil variables (Fayolle et al., 2019b; Spangenberg and Zufferey, 2018). Average annual temperature is one of the main factors affecting wine quality. Extreme temperatures over 30 ˚C and higher can reduce the berry size and weight (Orduña, 2010). Also, it was described in previous studies that precipitation can change the berry size and influence the amount of sugar (Zsófi et al., 2011). Despite the previous studies on the climate conditions influencing wine industry, the result of the analysis in this study shows that the relationship between wine quality and climatic variables is low. Correlation analysis showed moderate negative and positive relationship for variables representing the temperature and solar radiation and low correlation for variables showing precipitation, but the analysis results

revealed that there are non-linear relationships between wine prices and climatic conditions. For example, wine prices reduce with too high and too low temperatures, when the suitable average annual temperature range for the high-priced wines is from 9-18 ˚C, and also, the proper summer temperatures for the production of the wines with high prices in from 15-25 ˚C. Also, there is a relationship with the precipitation during the ripening season and wine prices, which shows that the drier summer is, the higher the prices. Similar results were found in the previous studies and the results of correlation analysis prove the wine dependency on the environmental conditions (Baciocco et al., 2014; Bonfante et al., 2018; Jones et al., 2005; Orduña, 2010).

In the spatial analysis of wine growing regions, research questions as the funding the spatial patterns of wine quality and price and further identification of the regions with the highest wine quality and price were answered.

The results of the spatial analysis in this study indicate that the wine producing regions are located mostly in Mediterranean climate. There was a clear pattern of the districts with wine production. The closer analysis points out that the patterns with the highest wine quality are located in the well-known luxurious wine-regions all over the world, such as Bordeaux, Provence regions and Champagne in France, Andalousia and Catalonia in Spain, Tuscany, Sardegna and Sicily in Italy, for example. However, the quality-price ratio results showed that smaller viticultural regions have better quality and price rates. Thus, in the well-known regions, where premium wines are produced the wine quality is very high, so are the prices. But in some smaller viticultural areas highly-rated wines can also be found, but the prices are lower there. The results of the analysis for the North America indicate that the west coast of the country is rich for the vineyards, producing high-quality wines, when the rest of the country is mostly empty. Hot spot of the high-quality wines in USA is in California state. About 30 000 reviews are coming from this area. This can be explained by the origin of the dataset. Wine dataset was extracted from an American magazine “Wine enthusiast” and the reviewers are Americans. That’s why almost half of the wine reviews are in North America.

The regions with highest quality reviews were determined as the areas with the highest price rates, which can be explained by the premium vineyards, located in these districts. As it was underlined in previous studies, the price for the wine bottle is closely related to the reputation of the vineyard and the winery. If it is a unique prestigious wine like Bordeaux Haut-Brion, made from the rare kind of grape it can cost hundreds of dollars (Cardebat and Jiao, 2018; Sébastien Lecocqyand, 2003). For example, wine “Domaine du Comte Liger-Belair 2010 La Romanée”, which is Pinot Noir type from Burgundy region in France costed 2500$ per bottle in 2019. Now, the cheapest price for this wine is 3500$ and can be up to 8100$ per 750 ml bottle (https://www.wine-searcher.com). This may indicate that this vineyard has good reputation and can sell wines with higher prices or the rare type of the

grape, which was successfully grown in 2010 vintage year. Also, it could have been aged in French oak barrels, which production is expensive.

The other limitations of the data in this study must be considered. Vineyards were georeferenced using Google API, however, the location for some of the vineyards might not have been precise. Some of georeferenced data located in the middle of the country or province because neither Google API, Mapbox API, OSM API or manual search was not successful. Another uncertainty arises from the wine reviews. This data is presented on a 100-point scale but all the wine reviews had points only between 80 to100. This might mean that wine reviewers only rated relatively high all the wines. The results of the spatial patterns of high-quality wines are displaying the hot-spots of the luxurious vineyards, which have outstanding reputation all over the world, and the pattern of the big variety of good less expensive wines. As it was described in previous studies, the reviews can be subjective, as all people are different and have different preferences. Although, the reviews from the professional wine experts have special classification system, so these datasets have high reliability and can be used for scientific researches (Gokcekus et. al, 2019; Oczkowski, 2016b). But it is important to remember that there is no excellent measure for the wine quality.

Due to such data limitations in wine dataset and soil variables, the results of this research cannot be considered as the perfect reference. However, to get the better view on the wine quality correlation with soil and climatic variables, the other datasets can be examined, but the methodology can be analogous to the one used in this study.

Kokkuvõte

Magistritöö: Veini kvaliteedi ja hinna ruumiline varieerumine ning nende seosed kliima- ja mullastikunäitajatega

Selles uurimuses keskendutakse veini kvaliteedi ja hinna ruumilistele mustritele. Analüüsitakse ka nende muutujate korrelatiivset seost kliima- ja mullastikutingimustega eesmärgiga tõestada, et need muutujad mõjutavad veini kvaliteeti, kuna varasemates uurimustöödes on viidatud, et need on peamised veiniviinamarja koostise arengut mõjutavad tegurid ning neil on otsene mõju veini kvaliteedile (Abbal et al., 2019; Gergaud and Ginsburgh, 2019; van Leeuwen and Darriet, 2016).

Seega on uurimustöö eesmärk selgitada välja, kas veini kvaliteedi ja keskkonnatingimuste vahel on seos, ning tuvastada kas veini kvaliteedil ja hinnal esineb ruumiline muster. Selle eesmärgi saavutamiseks püstitati järgmised uurimisküsimused:

- tuvastada veini kvaliteedi ja hinna ruumilised mustrid;
- selgitada välja parima kvaliteedi ning kõrgeima hinnaga veinide piirkonnad;
- määrata kindlaks, kas veini kvaliteedi/hinna ning kliima- ja mullastiku muutujate vahel on seos.

Andmestik, mis koosneb veiniarvustustest saadud andmetest ning hõlmab veinide hindu ja kvaliteedipunkte, saadi veiniajakirjast „WineEnthusiast“ ning oli .csv-formaadis tabelina kasutatav. Andmestik koosnes ligikaudu 130 000 reast, kus iga rida tähistas ühte veiniarvustust. Veiniandmed geokodeeriti ning uurimustöös kasutatud kliimaandmed saadi allikast Wordclim version 2. Mullastiku andmed võeti andmebaastist SoilGrids..

Veini kvaliteedi ja hinna ruumiliste mustrite leidmiseks kasutati ruumianalüüsi meetodeid. Erinevatele viinamarjakasvatuspiirkondadele loodi kuusnurksed võrgustikud ning veiniandmeid sisaldavad punktid koondati kuusnurkadesse. Selleks viidi läbi statistiline analüüs, arvutades „keskmise“ veini kvaliteedi ja „standardhälbe“ väärtused.

Leidmaks seoseid veini kvaliteedi/hinna ning kliima- ja mullastikutingimuste vahel kasutati korrelatsioonianalüüsi.

Ruumilise analüüsi tulemused näitasid, et parima kvaliteediga veini tootmise piirkonnad on ka üle maailma tuntud veinitootmispiirkonnad, näiteks Bordeaux’, Provence’i ja Champagne’i piirkonnad Prantsusmaal, Andaluusia ja Kataloonia Hispaanias, Toskaana, Sardiinia ja Sitsiilia Itaalias.

Leiti, et veini kvaliteedi ja keskkonnamuutujate vahel on väga nõrk korrelatiivne seos, seega ei saa selle andmestiku põhjal öelda, et kliima- ja mullastikunäitajad onveini kvaliteediga seotud. Samas tuvastativeinihindade ja kõigi kasutatud keskkonnamuutujate vahel on mittelineaarseid seoseid.

Osaliselt võib nõrku statistilisi seosed põhjendada kasutatud andmete piiratusega. Näiteks, veini kvaliteediandmed olid esitatud 100-punkti skaalal, ent kõigi veiniarvustuste punktisummad jäid vahemikku 80-100, seega analüüsiti ainult suhteliselt häid veine. Kvaliteediarvutuste autorid ei olnud ka elukutselised veiniarvustajad, hinnad olid aga määratud tootjate poolt, kes on veinitööstuse spetsialistid. See võis olla põhjuseks, miks veini hind andis paremaid seoseid. Mullastiku ja kliimaandmestikud ei olnud väga hea ruumilise lahutusega ja seega ei pruukinud kõikide viinamarjaistanduste tegelikke olusid õigesti peegeldada.

Kokkuvõtteks võib öelda, et selle uurimustöö tulemuste tõlgendamise võimalused on piiratud uurimustöös kasutatud andmestike tõttu. Nendele piirangutele vaatamata leiti uurimisküsimustele vastused ja tuvastati viinamarjakasvatuspiirkonnad, kus toodetakse parimaid veine. Ehkki korrelatsioonanalüüsi tulemused ei näidanud peaaegu mingit veini kvaliteedi ja keskkonnamuutujate vahelist seost, leiti samas arvestatavad seosed veini hinnaga.

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Annex. List of climatic variable abbreviations

Abbreviation	Full form
Annual mean t°	Annual mean temperature
Min t° coldest m.	Minimum temperature of the coldest month
Max t° warmest m.	Maximum temperature of the warmest month
Average summer t° in NH	Average summer temperature in Northern Hemisphere
Average summer t° in SH	Summer precipitation in Southern Hemisphere
Annual precip.	Annual precipitation
Summer precip. NH	Summer precipitation in Northern Hemisphere
Summer precip. SH	Summer precipitation in Southern Hemisphere

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