Vineyard Characterization across Continents: GIS and Remote Sensing Insights into European and South American Environments

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In partial fulfillment of the requirements for a degree in Geographic Information Systems and Remote Sensing in Environmental Sciences

By

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Objectives of thesis

Viticulture, the art and science of grape cultivation, is a fundamental pillar of the global wine industry. Europe and South America are two prominent continents in the viticulture world, each with a long history of producing wine. This thesis aims to use Remote Sensing (RS) and Geographic Information Systems (GIS) to analyse and contrast the grape landscapes of Europe and South America. The aim is to pinpoint the spatial patterns and environmental factors influencing viticulture in these two areas using satellite imagery, environmental parameter assessment, and spatial data analysis. The study aims to understand the factors influencing vineyard landscapes, topographical, climatic, and vegetation differences, and their implications for viticulture and vineyard management.

Methodology

The methodology for this thesis involves:

Selecting vineyards for study;

Obtaining and preprocessing data;

Creating topographical features;

Calculating vegetation indices;

Collecting weather data;

Conducting statistical analysis.

Data sources include Sentinel-2 imagery for recent years, seasons relevant to vine growth cycles, and Digital Elevation Models (DEM) for topographical analysis. Preprocessing includes atmospheric correction, cloud removal, and masking. Topographical features such as watershed, hillshade, aspect, slope, topography position index, and solar radiation are calculated. Vegetation health will be assessed using indices like NDVI, SAVI, MSAVI, and NDWI. Weather data will be collected and analyzed to understand climatic impacts, and statistical methods, including correlation, linear regression, MANOVA, Pearson correlation, time series analysis, and PCA, are used to interpret the data and identify patterns and relationships in vineyard health and productivity.

The proposed extent of the thesis

30-50 pages

Keywords

Topographical Features, Climatic Conditions, Vineyard Management Practices, Sentinel 2, Soil types, Grapevine varieties, Seasonal differences, Adaptive strategies

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Recommended information sources

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Author’s statement

I hereby declare that I have independently elaborated the bachelor thesis with the topic of Vineyard Characterization across Continents: GIS and Remote Sensing Insights into European and South American Environments and that I have cited all of the information sources that I used in the thesis as listed at the end of the thesis in the list of used information sources. I am aware that my bachelor/final thesis is subject to Act No. 121/2000 Coll., on copyright, on rights related to copyright, and on amendments of certain acts, as amended by later regulations, particularly the provisions of Section 35(3) of the act on the use of the thesis. I am aware that by submitting the bachelor/final thesis I agree with its publication under Act No. 111/1998 Coll., on universities and on the change and amendments of certain acts, as amended, regardless of the result of its defense. With my own signature, I also declare that the electronic version is identical to the printed version and the data stated in the thesis has been processed in relation to the GDPR.

Hakan Erim / Prague / 20/03/2024

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His constructive feedback, coupled with an open-door policy, provided me with the confidence to navigate the complexities of this study. His profound knowledge and insightful critiques have significantly shaped this thesis, pushing me to think critically and to approach my research from innovative perspectives.

For all these reasons and more, I am immensely thankful for Ing. Jan Komárek Ph.D.'s contribution to my academic and personal growth. It has been an honor and a privilege to work under his supervision.

Abstract: Viticulture, the art and science of grape cultivation, is a fundamental pillar of the global wine industry. Europe and South America are two prominent continents in the viticulture world, each with a long history of producing wine. This thesis aims to use Remote Sensing (RS) and Geographic Information Systems (GIS) to analyze and contrast the grape landscapes of Europe and South America. The aim is to pinpoint the spatial patterns and environmental factors influencing viticulture in these two areas using satellite imagery, environmental parameter assessment, and spatial data analysis. The study aims to understand the factors influencing vineyard landscapes, topographical, climatic, and vegetation differences, and their implications for viticulture and vineyard management. Data sources include Sentinel-2 imagery for recent years, seasons relevant to vine growth cycles, and Digital Elevation Models (DEM) for topographical analysis. Preprocessing includes atmospheric correction, cloud removal, and masking. Topographical features such as watershed, hillshade, slope, and topography position index, are calculated. Vegetation health is assessed using indices like NDVI, SAVI, MSAVI, and NDWI. Weather data is collected and analyzed to understand climatic impacts, and statistical methods, including correlation, linear regression, MANOVA, Pearson correlation, and time series analysis are used to interpret the data and identify patterns and relationships in vineyard health and productivity.

Key Words: Adaptive strategies, Climatic Conditions, Geographical Information Systems, Grapevine, Management, Normalized Vegetation indices, Practices, Process, Remote Sensing, Seasonal Differences, Sentinel 2, Soil, Topographical Features, Vegetation, Vineyard, Viticulture, Waterflow

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1. Introduction

Viticulture, which is not only an agricultural activity but also a hobby for some people, is an economic factor and maybe even the main reputation of a country. Like the business aspect, vineyard management is receiving increased attention in light of growing wine demand as well as the vital importance of terroir to the wine produced. Europe and South America are two of the world's most important wine-producing continents. Both regions have developed different viticulture traditions and practices. European settlers and merchants brought wine traditions with them when they first arrived in South America. These two regions are milestones of viticulture practices with long histories of wine production with their diverse grapes selection. Several simple observations can be made that are important to understanding the very real variety in terroir and viticulture practices that lay beneath those reputations. Europe has been associated with the farm settings that originally characterized its vineyard landscapes, while South America is rapidly gaining an international reputation for unique vineyards and wine production technology. Wine is not just a drink for Europeans. The wine business stands for many people to earn their main income. It's a pillar of economic growth, a cultural legacy, and a testament to the diverse terroir of the Europe[1].

South American wine is rich and diverse. Indeed, South America inherits its viticulture from Europeans. European colonization introduced wine to South America. Its quick rise to become a top region in viticulture is a hard work of viticulture in South America itself[2]. But more than for the quality of wines it produces, this continent has recently become famous for developments for viticulture itself. In the great wine perspective, South American vineyards are the new piece of old habits and innovations where winemakers are willing to practice with the latest technologies. South American viticulture has come to be known on the world stage for its harmonious terroirs, and innovations[3]. They take an important place in the wine production globally, with each geographical features and cultural significance of each, Europe and South America provide us best experiences. It is important to not forget that viticulture is an important economic factor[4]. Remote sensing technology (RS) and Geographic Information Systems (GIS) can be important tools to analyze and compare the vineyards of South America and Europe. Even though, there are research about analyzing vineyards by using RS and GIS technologies (Weiss, M., & Baret, F. (2017) and Hall, A., & Wilson, M. (2013)). This thesis directly focuses on finding similarities and differences between two major wine-producer continents, the aim is to detect spatial patterns, and topographical features that can influence vineyard management by using satellite imagery, environmental parameter assessment, and spatial data analysis in these two vineyard regions. In the end of this thesis research, we should have a better understanding what are different factors that can change grape qualities. It will contribute to the wider discussion regarding viticulture patterns and regional characteristics. The importance of GIS and Remote Sensing will be understood one more time with this thesis.

[1] https://www.wineinmoderation.eu/culture/history-and-tradition
[2] https://savagevines.co.uk/south-american-wine/
[3] https://southamericawineguide.com/winery-guide-south-america/
[4] https://wineamerica.org/economic-impact-study/2022-american-wine-industry-methodology/

2. Objectives

This thesis aims to do a complete assessment of vineyards in two different continents – Europe and South America, by using GIS and RS technologies. The goal is to identify the actual similarities and differences in the topographical features, climatic conditions, and vegetation indicators of four vineyards (two in Europe and two in South America). The objectives are listed to contribute to a better and wider understanding of viticulture in different environmental conditions and to observe the challenges of vineyard characterization.

Objective 2.1: To Assess and Compare the Topographical Characteristics of the Selected Vineyards

Evaluating of the topographical characteristics of selected four vineyards is the first goal. These steps include using GIS technologies and digital elevation models (DEMs) to analyze terrain features such as elevation, slope, and aspect. The objective will help us to understand and observe how these topographical features impact vineyard microclimates and grapevine growth in the disparate locations of Europe and South America.

Objective 2.2: To Analyze and Contrast the Climatic Conditions Affecting the Vineyards

Examining the climatic factors that might affect vine development and health in the chosen vineyards is the goal of this purpose. This step will analyze temperature regimes, and precipitation patterns, using meteorological records. A comparative study of the vineyards will illustrate us the climate-related effects and relations that characterize the unique viticultural characteristics of each area.

Objective 2.3: To Evaluate Vegetation Indices as Indicators of Vineyard Health and Vigor

By using RS technologies, this objective focuses on observing vegetation indices, to understand vineyard health and vigor. The analysis will determine spatial and temporal differences in vegetation health between the vineyards by providing insights into the effects of environmental conditions on vine productivity and grape quality.

3. Literature Review

RS and GIS are pieces of the puzzle. They can complement each other in many fields. When the economic and cultural importance of viticulture is considered, development is always needed to keep quality and heritage of it. To contribute Remote Sensing and GIS have been used several times for viticulture-related purposes. These two tools enhance the precision of viticulture and can give beneficial results. Hall et.al (2002) analyzes optical Remote Sensing in viticulture applications. This study gives us a better overview of agriculture technologies, especially remote sensing, for improved monitoring and management of vineyards. It uses RS technology to enable us to distinguish shape, size, and vigor cover in vineyards and it tells us Remote Sensing's potential to revolutionize old viticulture practices. Satellite images and UAV (Unmanned aerial vehicles) are used. They help authors to detect vegetation health, soil properties, and water status. A great relationship can be built between canopy cover and grapevine quality. The study aims to point out the future use of RS in viticulture. He proves the efficiency, sustainability, and profitability of vineyard management can get help from RS technologies.

Remote sensing does not only exist from satellites but also there are many RS technologies that we can use for vineyard management. Mazzetto et al. (2010) study for monitoring canopy health and vigor in precision viticulture by using optical and analog sensors. They explore potential results of RS information obtained from RS technologies placed in vineyards directly. Researchers developed a mobile lab equipped with two GreenSeeker RT100 sensors. Those are optical devices that calculate NDVI and NIR indices at the same time. Six ultrasonic sensors to detect canopy cover are used. DGPS collected geo-referenced data across the vineyard. Results show that NDVI values are high. Optical data for NDVI shows the canopy vigor evolution between some of the vineyards that are treated and untreated. Ultrasonically measured canopy thickness (UCT) is compared with manually measured canopy thickness. They show a strong correlation between each other. This can tell us that UCT can be a way to monitor vineyard conditions. This study tells us how optical and analog sensors are effective for precision in viticulture for real-time detection. Such RS technologies contribute to sustainable vineyard management.

Sassu et al. (2021) use another RS technology - UAV for the precision of viticulture. This study tells us application and development of UAVs in viticulture. UAVs can give better results thanks to their high precision and flexibility. It also provides low cost operation. UAV is being a main and indispensable tool for viticulture management. This study focuses on row segmentation, crop feature detection, vineyard variability monitoring, disease detection, estimation of row area and volume, and the creation of vigor and prescription maps. This approach can easily tell us that UAV technology can address a wide range of scope for viticulture. The paper suggests that UAVs will have a significant role in the future of viticulture thanks to their ability to meet the current demand for digital technology integration in agricultural practices.

Johnson et al. (2012) investigate whether satellite images can improve viticulture activities. This research highlights how those images contribute to viticulture after spatial data is analyzed with GIS tools. It is understood that RS and GIS can be important tools for improvement. Remote sensing helps in mapping vineyards geographically. When remote sensing data with other spatial information and a GIS is integrated, it enables the detailed analysis of vineyard variation and assists precision agriculture practices. Moreover, one of the other key points is Grapevine canopies may be spotted by RS. This study also shows some examples of Remote sensing operations that are developed in vine-growing regions. What can be concluded from this research is remote sensing technologies can advance viticulture practices, it can develop vineyard management, and support the production of high-quality wines by monitoring the condition of vineyards.

The contribution of GIS and Remote Sensing to viticulture cannot be denied. However, it is important to know about challenges as well. The viticulture process is quite sensitive and many things can impact it**.** Sapaev et al. (2023) investigate challenges in viticulture. A few of the challenges are atmospheric conditions, drought, heat waves, labor shortages, and rising production costs. Researchers explore potential solutions for those challenges. Perhaps, digital technologies can be the primary solution. But the main question is how those advancements could provide a great solution by improving the vine sector’s resilience to environmental obstacles. Researchers examine the application of remote sensing which has given us a better understanding of vineyards' variabilities in terms of geographical dynamics. Viticulturists have used RS technologies to apply critical interventions and make important decisions for fruit harvesting based on yield and quality requirements. Adoption of such digital technologies contributes not only to reducing input costs and improving the efficiency of operations but also to developing the end product's quality. However, this technology can bring disadvantages as RS technology can dismiss privacy and security especially when third parties are involved.

As mentioned, climate is an important factor for viticulture activities. Fraga et al. (2012) investigate the impact of climate change on European viticulture. Climate plays an important role in the success of viticulture and the quality of the process. It is found that temperatures show an increase during the growth season of grapes. These changes are expected to continue and even increase in the future since there is a big difference between temperature and precipitation patterns. This study explains how important it is that the viticulture sector should adapt to the changes and take necessary measures to align with expected climate changes. Short-term strategies can be considered as quick measures to specific threats. Changing crop management practices such as irrigation and sunscreens for leaf protection can be counted as one of the few measures. However, this study issues that a detailed long-term adaptation measure will be critical to sustaining wine production and quality against climate change. Land modification might be necessary for it. It is concluded that viticulture in Europe should develop itself to sustain its heritage and quality.

Meanwhile, climate change is showing itself to us and already impacts viticulture, GIS and RS are indispensable for the practices for keeping good quality grapes. Kingra et al. (2016) search for important edge technologies. Especially Remote Sensing, GPS, and GIS. Those technologies can be useful against complex challenges of agricultural production and resource management caused by climate conditions. This research shows how agriculture is sensitive to climate conditions and topographical features. Application of GIS and RS can help us to discriminate and monitor such vegetation health and moisture detection. Important decisions, such as accurate assessment and crop management as well as using natural resources, can be decided more precisely by using these applications. Managers and producers can manage the security of viticulture by considering the economic impact of agriculture practices. Hence GIS and RS are valuable in land use analysis and detecting damages from drought floods and other extreme weather events. Climatic change scenarios can be foreseen and necessary measures can be taken on time.

Knowing viticulture is as important as applying GIS and RS sensing technologies. Without having enough knowledge about vineyards, it is quite impossible to apply useful practices to them. A.J. Winkler et al. (1974) is an important resource in the viticulture field. It gives essential information for grape cultivation. It provides detailed knowledge about viticultural practices. It mentions grapevine biology and other environmental factors such as topography that can influence grape production and management of vineyards. Authors give us huge knowledge and they offer ecological principles that can affect grape growing. Vine structure, soil and pest management, grape variety selection and the impact of climate change on grape development are discussed. Even though, this book was published 50 years ago, the principal in this book stay remains for today. However, it is good to note that the new technologies are not covered in this book such as new pest management, irrigation systems, and practical viticulture management. This resource essentially is a very precious resource for everyone who has an interest in viticulture practices.

There are many types of research about viticulture management and what effects viticulture. As it is said, RS and GIS can give us insightful information about viticulture. However, it is important to realize how to use RS and GIS. Without any data, we cannot use such technologies. Devaux et al. (2019) use Sentinel-2 satellite images to monitor vine growth during the entire season. This study aims to identify the main stages of Mediterranean vineyard development. A vineyard in southern France is used for the study area. It captures images during the growing season of 2017. NDVI is calculated and a time series of it is created to observe weed management practices. The results show us that usable images were every 16 days due to satellite availability issues. Sentinel-2 is useful to identify potential vineyard development stages. However, satellite image resolution can be a disadvantage for small vineyard blocks. This study characterizes vineyard blocks and monitored practices on a territorial scale. That detailed NDVI time series provides information about vineyard management and highlights this area for future research. The development of new indicators can be useful for understanding the vineyard and climate relationship.

It is known that topographical features are important for vineyards, as they can affect microclimates. To proceed with spatial analysis of the topographical features of vineyards, it is important to know where to acquire the data. Rodríguez et al. (2006) analyze the evaluation of the Shuttle Radar Topography Mission and its data quality and its applications. SRTM by NASA aims to produce high-resolution digital elevation models (DEM). This mission uses synthetic aperture radar (InSAR) technology. Authors investigate technical aspects of SRTM, for example, its data collection and processing. It is validated that DEM gives less than 16 meters of vertical error of 90% of the data. One of the great results of this research is that SRTM can be used in many fields. These are Hydrological modeling, land cover mapping, and geological and environmental research. SRTM data was successfully used in those fields. With all those advantages, SRTM can bring some disadvantages as well. The SRTM dataset has challenges with radar shadowing and foreseeing. In dense vegetation areas or steep terrain. SRTM is significant for landmark projects for RS. It provides essential resources for search, as well as detailed elevation data. The authors evaluate the performance of SRTM and see the success of the mission. It contributes to understanding Earth’s topography and its impact on Geospatial sciences.

Yang, Meng, & Zhang (2011) also investigate SRTM DEM and its application advances. Authors are discussing about technical advantages of SRTM. The advantages are its principles, dataset characteristics, and the accuracy of the elevation data. The strength of this research is the detailed exposition of SRTM DEM's applications in a wide aspect of research areas. With this strength, SRTM can address complex environmental and geological needs. However, of course, there are some challenges detected in this study. Future research and adding depth to the review, highlight areas that can enhance the utility of SRTM DEM in scientific research. More detailed comparisons between other DEMs could be useful for this research. For example, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) GDEM or Light Detection and Ranging (LiDAR)-based DEMs. These comparisons can enable readers to realize the strong side of SRTM and the challenges compared to other DEM tools. As this study is released in 2021, there are more advancements in RS technology with new data algorithms. Overall, Yang, Meng, & Zhang's review of this article is a great source for researchers who are interested in the applications of SRTM DEM and its use for a range of environmental and GIS, and RS disciplines. It shows the important role of SRTM DEM.

Thanks to high-quality DEMs, we can process many topographical data which are crucial for understanding vineyard characteristics. Reu, et al (2013*)* apply the topographic position index (TPI) to heterogeneous landscapes. This paper studies the utility of TPI by landform classification across different landscapes. This study takes place in Belgium. It reveals that as long as the use of TPI increases to measure topographic slope positions. Researchers investigated if deviation from mean elevation (DEV) can be a better method for landform classification. It is found that DEV provides a better and more correct geomorphological assessment for their study fields. This study gives us another approach to landscape classification. It tells us the effectiveness and importance of TPI but proposes the application of DEV at the same time as well. Both approaches are critical for analysis in heterogeneous landscapes.

When we collect all the data, it is time to decide which analysis to use. Vegetation indices are great indicators for detecting vegetation health. Research by Rondeaux et al. (1996) checks the limitations of NDVI as it is sensitive to soil background and atmospheric conditions. More reliable vegetation indices can offer better performance under those specific conditions. The authors provide Soil-Adjusted Vegetation Index (SAVI), Transformed Soil-Adjusted Vegetation Index (TSAVI), Atmospherically Resistant Vegetation Index (ARVI), Global Environment Monitoring Index (GEMI), and Modified Soil-Adjusted Vegetation Index (MSAVI) as alternative options. This study approaches to evaluate the detailed performance of these indices against a wide range of soil grounds. It includes many soil types such as sand, clay, and dark peat, under different moisture and roughness conditions. The authors optimize the X value which is important to minimize soil effect in the calculation. This study offers a clear and systematic evaluation of how each index responds to soil background effects. It shows the importance of other alternative vegetation indices besides NDVI. However, it would be great if this study could be enhanced with newer research. New cases or applications that apply the practical utility of these indices in various environmental and agricultural settings would be a great asset for this research. In conclusion, this research is really important as it makes a great contribution to the field of remote sensing by addressing the critical need for more reliable vegetation indices that are less sensitive to external influences

Another research by Qi et al (1994) is also focusing on the weaknesses of NDVI and developments in the RS sector. NDVI brings sensitivity to external factors such as soil background and atmospheric conditions. That requires more development of vegetation indices. MSAVI is aimed to enhance vegetation analysis with soil adjustment factor L. MSAVI can adjust dynamic soil effects depending on vegetation present so that it can reduce soil effect background effects. This method gives us more sensitive and accurate patterns. This study uses aircraft-measured cotton canopies which illustrates the practical application and effectiveness of MSAVI in different environmental settings. This paper also proves that there is a good alternative for NDVI which is a standard analysis approach for most studies. The development of MSAVI and its ability to increase vegetation signal sensitivity is significant. Noise from the soil background is a great way the use remote sensing data for vegetation analysis.

NDVI's disadvantages are mentioned in many researches. But, doesn't it have any contribution to viticulture analysis? Johnson, L. (2003) explores the connection of NDVI and leaf area in vineyards which are in Napa Valley during the 2001 growing season. He uses Ikanos satellites which are high-resolution. He compares NDVI values and ground-measured LAI (Leaf area index). He finds a strong correlation between these two values. The correlation is between 0.91-0.98. He applied linear regression and he observed that this strong correlation became stable. This correlation can tell us that NDVI is a great indicator for LAI in viticulture management. This result can be helpful for viticulture managers and they can do cost saving by reducing groundwork. This research tells us one more time that Remote Sensing is crucial to monitor vineyards especially in the growing season.

Grapes are quite sensitive to Irrigation and moisture. Even small changes in water quality/quantity can change the quality of grapes and wine itself. Gao (1996) introduces NDWI as his approach to detecting vegetation's water level. NDWI is important for detecting the water content of the vegetation. Gao has used NDVI to create a better understanding impact of water levels. NDWI enables us to advance our monitoring for Remote Sensing and agricultural monitoring. NDWI is sensitive to changes in vegetation water cover and less impacted by atmospheric effects. We can see that NDWI is quite useful after Gao's field data analysis. NDWI is also compared with NDVI. This can give us an approach method that water content and vegetation health can collaborate together. We again see importance of this methodology which can make us target the biophysical features of the vegetation.

A good statistical analysis approach is needed when so many indices are compared between different vineyards. Tukey, J. W. (1949) works on Comparing individual means in the analysis of variance (AOV). He gives us more detailed knowledge about the analysis of variance excluding basic F-or Z- test results. Tukey offers a direct process for dividing groups to understand the differences. Which allows better results during single-factor effects. This work is great in many perspectives as it offers a great approach for AOV. It goes more than whether mean values are different or not. It gives a method for possible grouping of these mean values. Tukey's approach hosts a more insightful for understanding statistical data. It identifies treatments that are similar or different. This provides better interpretations of the results. The conclusions from this study are a milestone for statistical analysis. Tukey has significantly contributed and developed a new methodology for future studies.

4. Methodology

4.1 Selection of Study Sites:

This strategic methodology intended to comprehend the various viticultural landscapes between continents — more especially, to compare the environments of Europe and South America — was used to help choose the vineyards for this study. The selected vineyards, Châteauau in France; Canelones in Uruguay; Cafayate in Argentina; and Tenuta San Guido in Italy, were selected using a set of standards that guarantee a thorough examination of viticultural, meteorological, and geographic factors. These factors include the vineyard's historical value, varietal diversity, terroir representativeness in the area, and the accessibility for remote sensing and GIS data collection. Each of the vineyards was evaluated based on its historical value about the surrounding area. A vineyard's depth of historical background can provide information on how important those areas are for viticulture. Some methods might have changed over time in response to climate shifts and advances in technology. When choosing each vineyard, the terroir of the area was one of the important considerations. The distinct blend of soil, temperature, and topography known as terroir, which shapes a wine's personality, differs greatly between viticultural areas.

Overview of Château Bordeaux Vineyards

The Bordeaux region, which is known for its extensive vineyards and rich viticultural history, is home to a range of châteaux that represent the region's wine-making legacy. It also makes a substantial contribution to the global wine industry. The vineyards at Château Bordeaux are notable for their advantageous location, which benefits from the Mediterranean climate and rich soil that are perfect for viticulture. All of these elements work together perfectly to produce wines that are of extraordinary quality. That makes Bordeaux wines extremely popular throughout the world. The uniqueness of Bordeaux's wines is featured from the combination of soil and climate that define the terroir of the Château vineyards. The diversity in soil types in the region, which are gravel, limestone, and clay, has an important role in the terroir expression of Bordeaux wines. Bordeaux enjoys a marine, Mediterranean, and moderate climate thanks to its location near the 45th parallel. Because of its advantageous location, the average annual temperature is 13°C with occasional highs of 35°C or even 40°C during the hottest summer months [5]

[5] (https://bordeaux.guides.winefolly.com/terroir/)

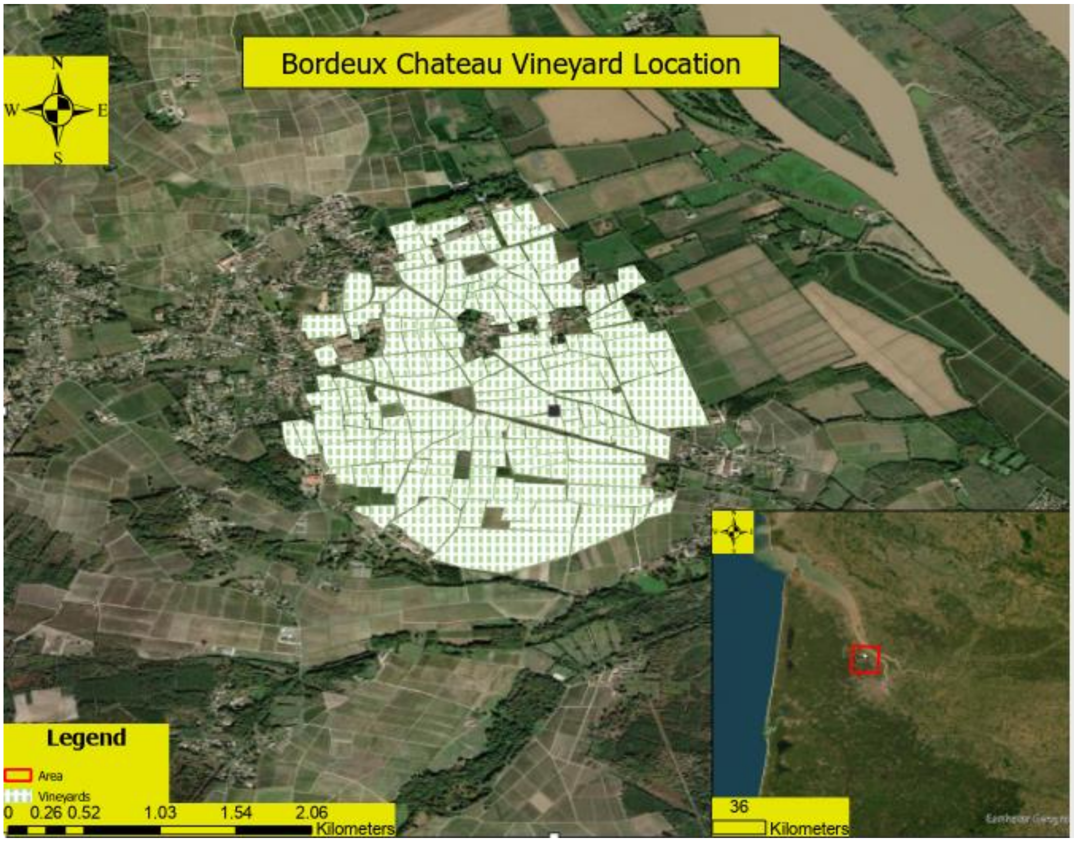

Figure 1: Map of Selected Study Sites in Chateau

Overview of Tenuta San Guido Vineyards

Tenuta San Guido, located in Sassicaia, hosts unique terroir qualities and a leading role in establishing the top Tuscan wines. This place enjoys a long growth season with warm days and mild nights thanks to the Tyrrhenian Sea's impact. The soil composition of the vineyards is rich and consists of sand, gravel, and clay. This soil composition makes it possible to grow vines with great qualities, which adds to the complexity and richness of the wines produced. Mario Incisa della Rocchetta is the one who should be credited with starting the vineyards here. Following World War One, he had an idea to produce a wine in Tuscany. Following his investigation, Cabernet Franc and Sauvignon Blanc were planted on the stony hillside plots of Castiglioncello di Bolgheri. Achieving the intended wine profile required careful consideration of location, with a focus on greater altitude and rocky terrain. Although Tenuta's first commercial vintage was released in 1968, the wine didn't reach its reputation as a world-class wine until it gained widespread recognition in the late 1970s and early 1980s, earning a 100-point rating from Robert Parker for the 1985 vintage. Advanced viticultural methods are used here. Owners consider environmental responsibility and sustainability. To preserve the ecosystem of the vineyards, organic agricultural methods instead of chemical-based fertilizers and pesticides are used. [6]

[6] (https://www.tenutasanguido.com/en/sassicaia-en, https://magazine.winerist.com/the-story-of-sassicaia-italys-first-super-tuscan/)

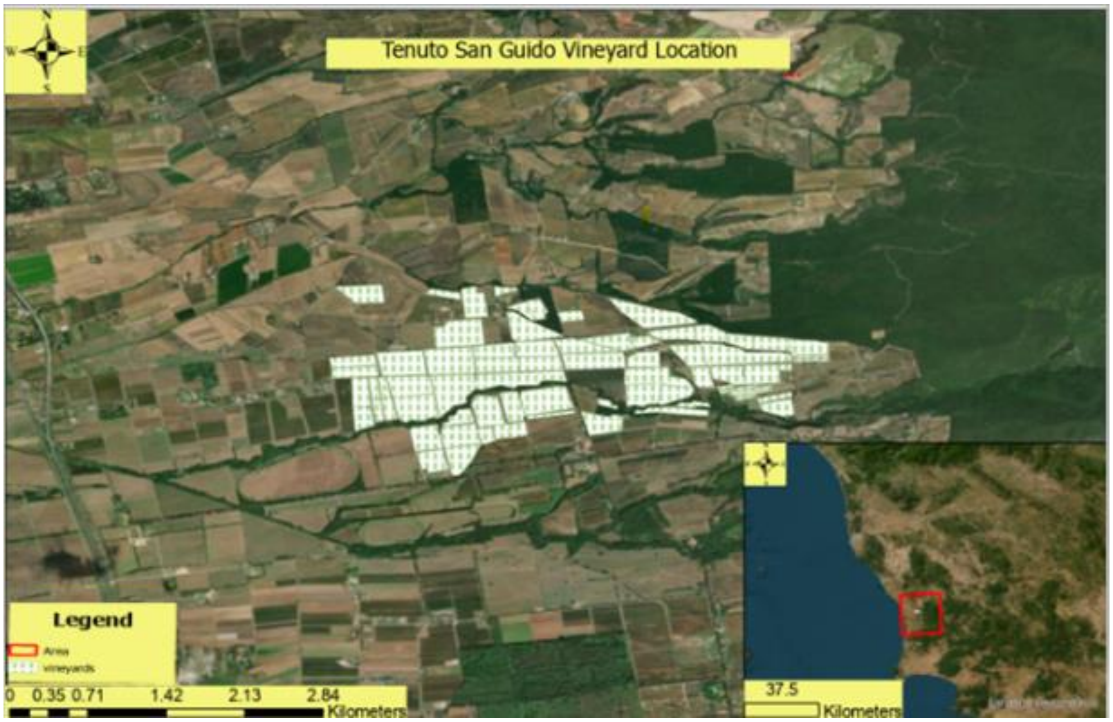

Figure 2: Map of Selected Study Sites in Tenuta

Ooverview of Cafayate Vineyards

Cafayate vineyards are situated in the Salta region of Argentina, which are located in high spots. Tough, vineyards are situated near the Equator, the Cafayate wine area owns a highly demanded viticulture industry due to the ideal combination of land and temperature. Because of this particular height, there is a noticeable difference in temperature between day and night, which can be advantageous for the formation of grape skins and produce wines with stronger, more concentrated tastes. The Cafayate wine region is mostly made from sandy loams with good drainage. Because of the fact that precipitation is low, the soils are naturally very dry. So irrigation practices are very critical here. Stronger wines are made from highly concentrated grapes with thicker skins that are produced in vineyards with this kind of terroir.

Torrontes grapes grow particularly well in the terroir of the Cafayate wine area, producing a crisp, fruit-forward white wine. When it comes to red wines, Tannat, Cabernet Sauvignon, and Malbec grapes provide full-bodied wines with a deep, nuanced structure[7]

[7] (Cafayate Wine Region, Argentina | Winetourism | Winetourism.com)

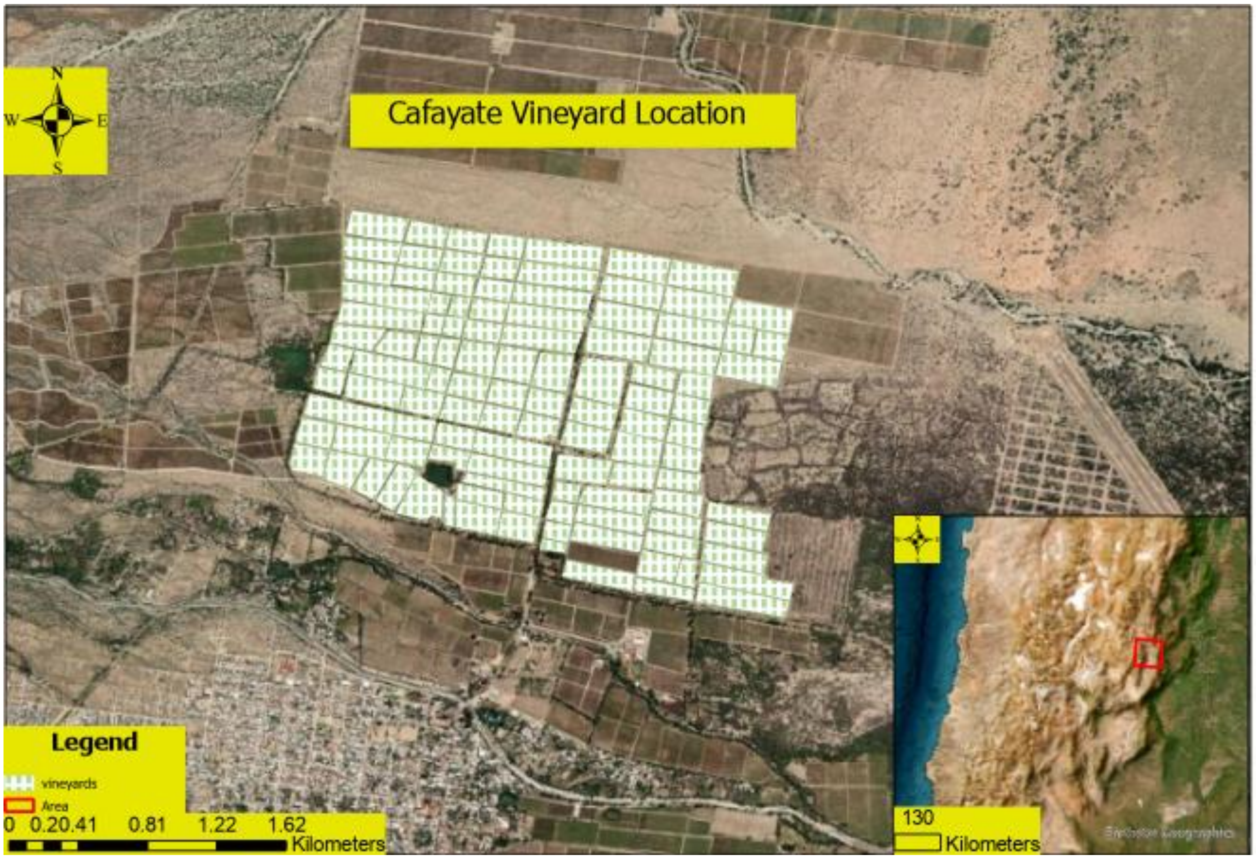

Figure 3: Map of Selected Study Sites in Cafayate

Overview of Canelones Vineyards

Canelones hosts the majority of Uruguay's vineyards. It lies northeast of the country's capital, Montevideo. The coastal environment of this region experiences warm summers and moderate winters. This is important to the terroir, which influences the taste profiles and attributes of the wines that are made. Small, family-run vineyards are main feature of this area. These small business add to the variety and excellence of its wine offerings. Fourth-generation winemakers, the Pisano family, emphasizes using traditional methods mixed with their ingenuity to create wines that honor their terroir and cultural history. In the late 1800s, European immigrants introduced viticulture to the Canelones wine area, and until the end of the 1800s, the region was producing its superior wines. The area is noted for its clay soil, which is good for vine development. [8]

[8] (Your 2024 guide to Canelones region | Winetourism.com)

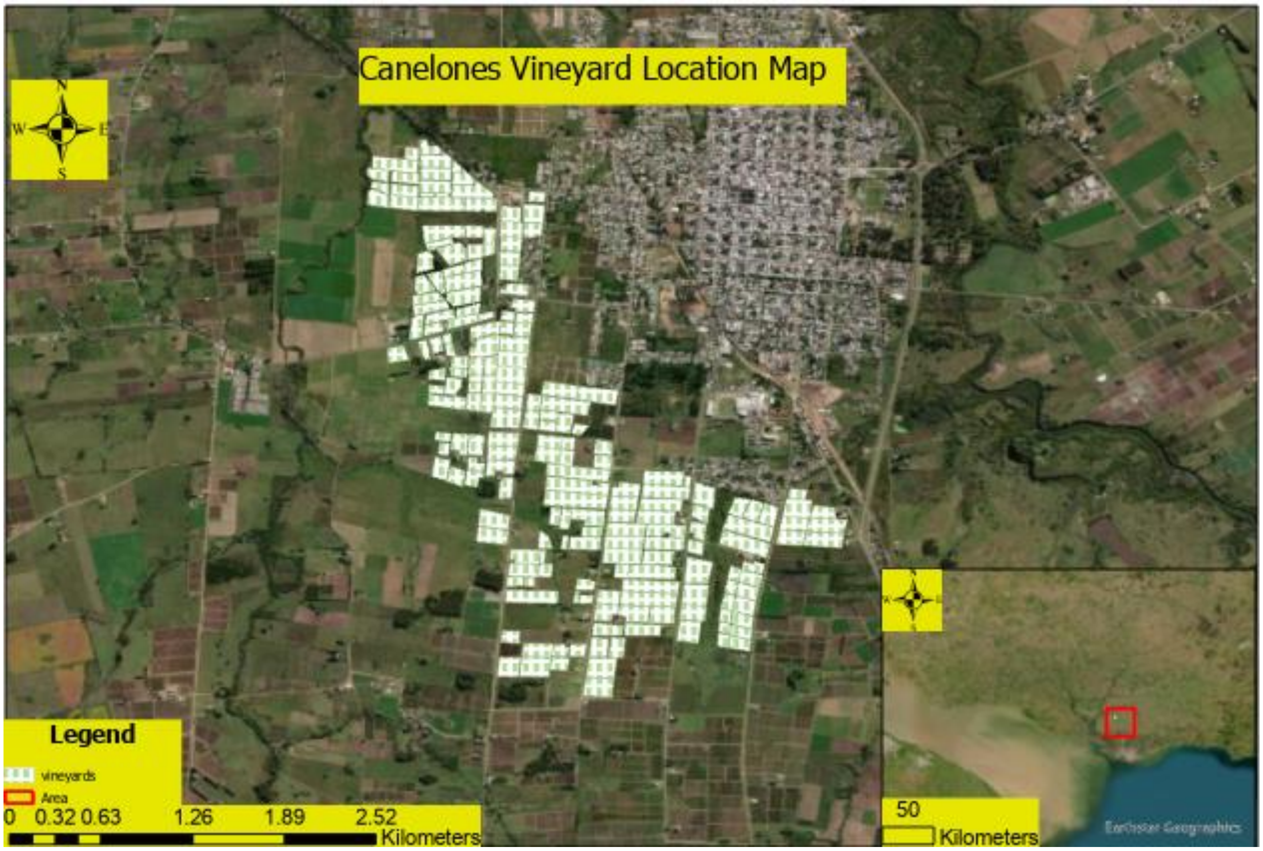

Figure 4: Map of Selected Study Sites in Canelones

4.2 Obtaining Materials:

Sentinel-2 is great choice for capturing vineyard images because of its ability to combine spectrum capabilities, frequent revisit times, and high spatial resolution which are essential for maintaining and monitoring vineyards.

Moreover, Sentinel-2 allows for frequent monitoring of vineyard conditions. It revisits five days or fewer under clear sky circumstances. This is important for monitoring changes during the growing season. Sentinel-2 is also effective for regional scale analysis and management strategies thanks to its 290 km swath width, which enables the capturing of huge vineyard areas in a single pass (Devaux et al., 2019)**.**

As it is indicated in research titled Comparing vineyard imagery acquired from “Sentinel-2 and Unmanned Aerial Vehicle (UAV) platform” by Sozzi et al. (2020), Sentinel-2 can be used for precise mapping and management of vineyards, because it can produce images with a high spatial resolution of 10 meters for both the RGB and NIR bands. This resolution is useful for tracking vine health and vigor at a good scale and for identifying vineyard variations. One of the other most important features of Sentinel-2 is that its included spectral design with red-edge bands makes it possible to calculate advanced vegetation indices such as Normalized Difference Vegetation Index (NDVI), which is critical for determining the health, vigor, and stress levels of plants. These metrics make precision viticulture possible by allowing for focused actions to raise quality and production. Finally, maybe the most convenient reason to use, Sentinel-2 is publicly accessible. All images for vineyards are downloaded from the Copernicus Browser.

Before downloading any images from those vineyards, it is crucial to know which seasons should be considered for grape growing. A.J. Winkler et al. (1974) provide important Insights such as on climate, phenology, and grapevine management to have a better overview of the viticulture season in Europe and South America. Fundamental concepts of viticulture are covered in the book. Understanding the differences between different wine areas in France and Italy requires knowledge about the idea of heat summation, which is introduced in the book and used to categorize grape-growing regions. For example, compared to colder areas, the warmer Mediterranean climate of Southern Italy and Southern France owns earlier bud break and harvest. By understanding and knowing the general viticulture, we can know that viticulture starts in spring and ends in autumn in Europe. The season of viticulture works the same in South America as well. It starts in spring and ends in autumn but it is important to notice that viticulture seasons follow the Southern Hemisphere's climatic cycle. This means September and November are part of spring and June and August are part of winter.

Sentinel-2 is a great way to acquire image data for calculating vegetation indices but when a topographical data image is needed, The Shuttle Radar Topography Mission (SRTM) provides very great contributions. The goal of the NASA-NGA partnership SRTM is to produce a reliable, error-quantified topographical dataset for areas up to 60° latitude **(**Rodríguez, Morris, & Belz, 2006). The processing and implementation of SRTM Digital Elevation Models (DEM) have advanced rapidly over the past ten years, having a major impact on a variety of sectors including hydrology, geology, and the assessment of natural hazards. The consistent quality and unrestricted access to SRTM have enabled these advancements (Yang, Meng, & Zhang, 2011). With all of those advancements, SRTM seemed the best way to acquire the Digital Elevation Model (DEM) of places where vineyards are located. All of the DEM data is downloaded from NASA Earth Data.[9]

When all datasets were ready to process, the last thing to do was ccreateshapefiles of the vineyard to apply masking to dataset and receive precise results from vegetation indices. First of all, exact polygons that represented the vineyard boundaries were manually drawn using Google Earth Pro's high-resolution satellite images, this technique made it possible to accurately and precisely capture the vineyard boundaries, guaranteeing an exact portrayal. After the polygon drawing procedure was finished, vineyard borders were exported as the Keyhole Markup Language (KML) format. Subsequently, the KML files were converted to the Shapefile (SHP) format in QGIS software.

[9](https://search.earthdata.nasa.gov.)

4.3 Pre-processing the Data

Another important thing to notice before calculating vegetation indices, which are downloaded data from Copernicus Hub, contained two different levels of Sentinel-2. Those are Sentinel-2 Level 1C and Level 2A. The Top of Atmosphere (TOA) reflectance values are given for the Level 1C data. This indicates that geometric and radiometric errors have been corrected for in the data by processing such as orthorectification and spatial registration to a global reference system. Nevertheless, atmospheric influences that may affect the reflectance values the satellite sensor receives are not taken into consideration in the data at this level. Hence, atmospheric correction algorithms should be used to improve as atmospheric correction has quite impact and importance for the data (Sola et al., 2018). On the other hand,in order to get Bottom of Atmosphere (BOA) corrected reflectance values, Level 2A data are processed. Atmospheric correction is applied at this processing level to mitigate the impacts of airborne gases, aerosols, and particles therefore no atmospheric correction is needed. To apply atmospheric correction to Level 1C data, The Rayleigh correction is used which is included as a tool in the Sentinel Application Platform (SNAP).

Finally, in order to reduce file size and the processing time of Sentinel imagery, a focused strategy was implemented by clipping specified zones of interest close to vineyard locations. By using ArcGIS's "Extract by Mask" feature, the satellite photos were carefully cropped to only include the regions surrounding the vineyards. This methodological step guarantees a targeted examination on pertinent segments, resulting in a significant reduction in data volume without compromising the accuracy of the information relevant to the vineyard evaluations.

4.4 Creating Topography Features of Study Areas

In order to provide a useful evaluation of the topographic impacts water flow dynamics and vineyard microclimates. Slope, hillshade, Topographic Position Index (TPI), and water flow maps were made and examined for this investigation. Using Spatial Analysis – Surface toolbox, each parameter was obtained from high-resolution digital elevation models (DEMs). Main approach was able to provide a picture of the physical environment influencing vine development and the quality of grape production. Purpose of creating the slope map was to determine how steep the terrain was in the vineyard areas. Slope affects solar radiation exposure, drainage patterns, and soil erosion rates, which are important factors to consider when choosing planting zones and management strategies for vineyards. To see which way the slopes are in the vineyard areas, I created an aspect map. Because aspect can influences microclimate conditions, such as temperature and moisture content. Thirdly, the hillshade model was created to replicate the shadows produced by topographical features in the absence of actual sunlight. This model makes the three-dimensional contour of the terrain more visible and indicates regions that might receive less sunshine, which could have an impact on vine growth and grape maturity rates. Additionally, TPI was calculated to distinguish landforms within the vineyard areas, categorizing the landscape into ridges, valleys, slopes, and flat areas[10]. This difference is critical to understand microclimate variations. Positive TPI values suggest that the location is positioned on a ridge or higher ground. Ridge positions have benefits such as improved drainage, better air

[10] (https://community.esri.com/t5/arcgis-pro-ideas/implement-topographic-position-index-as-a-tool-or/idi-p/921377)

circulation, and even potentially different microclimates. Less risk of frost damage can be observed in vineyards on ridges. Negative TPI values may indicate that the location is in a depression or lower ground. Areas in depressions may be more prone to waterlogging and could have different soil characteristics. TPI values around zero suggest flat terrain (Reu et al., 2013). Last of all, to see the patterns of surface water movement throughout the vineyards, a water flow map was made. Planning irrigations and controlling erosion effectively, Spatial Analyst -> Fill ->Flow Direction ->Flow Accumulation from ArcGis Pro toolbox is used to create water flow maps.

4.5 Calculating Vegetation Indices

Four vegetation indices (the Normalized Difference Vegetation Index (NDVI), the Soil-Adjusted Vegetation Index (SAVI), the Modified Soil-Adjusted Vegetation Index (MSAVI), and the Normalized Difference Water Index (NDWI)) were computed to evaluate the vegetative health and vigor within the vineyards. In viticulture, those indices are important for improving vineyard management, tracking plant health, and maximizing grape quality. These indices, which are a product of remote sensing technologies, provide insightful information about a range of vineyard conditions. All of these indices are calculated by using ArcGIS Pro software and SNAP software when needed. The importance of those indices and their formulas are below.

Normalized Difference Vegetation Index (NDVI)

By identifying the health of the vegetation, the NDVI is useful in evaluating the general health and vigor of vines. The viability of the vineyard can allow for focused management practices. Grape quality and vigor are strongly associated. NDVI is essential to precision viticulture practice because of its ability to forecast grape yield and evaluate vine health (Johnson, 2003). The calculation is based on the formula

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Soil-Adjusted Vegetation Index (SAVI)

SAVI is helpful in vineyards where there is sparse canopy cover. The soil background might distort the reflectance readings. SAVI changes NDVI to reduce the influence of soil brightness. This modification makes it possible to evaluate plant health more precisely, which helps determine whether irrigation or nutrient management is necessary to maximize vineyard yield (Qi et al., 1994). The calculation is based on formula L (Soil brightness correction factor), value is taken as 0.5 in this research as it is the common value. Unfortunately, there was no background knowledge to interpret another value for L.

$$SAVI = \frac{NIR - RED}{NIR + RED} \times (1 + L)$$

Modified Soil-Adjusted Vegetation Index (MSAVI)

MSAVI improves the correction for soil background even more by adding a soil brightness adjustment factor. It is useful for precise monitoring of grape vigor and health in diverse vineyards with different soil types and vegetation densities. Because MSAVI is more sensitive to vegetative indicators than SAVI, it can help with vineyard management decisions where there are different soil types (Qi et al., 1994). The calculation is based on formula

$$\frac{MSAVI = (2 \times NIR + 1\sqrt{(2 \times NIR + 1)^2 - 8 \times (NIR - RED)}}{2}$$

Normalized Difference Water Index (NDWI)

Water stress conditions can be analyzed by using NDWI. It is calculated to track the amount of water in vineyard vegetation. Vine moisture levels are measured using NDWI, which helps to optimize irrigation techniques so that vines are not overwatered or stressed by drought. Maintaining vine health and ensuring the production of high-quality grapes depend on this ideal water management (Gao, 1996). The calculation is based on

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR}$$

4.6 Collecting weather data

This part looks at how the weather can affect the performance of four those vineyards. Considering how important weather is to wine quality and grape production, a thorough meteorological data collection was conducted to guarantee an accurate assessment of climate influences. The national meteorological services listed below were used in order to gather the accurate climate data possible for each vineyard location:

- Météo-France
- Servizio Meteorologico of the Italian Air Force
- NOAA (National Oceanic and Atmospheric Administration)
- Servicio Meteorológico Nacional (SMN)
- Instituto Uruguayo de Meteorología (InUMet)

Since exact meteorological data for the years 2020 to 2022 are not found precisely, this thesis used a methodological technique that figured out the average weather patterns for every vineyard location. Average values for temperature, precipitation, and other relevant weather parameters were estimated based on the historical dataset. Missing values are estimated from other available years taking into consideration of average value of climate patterns and weather stats from neighboring cities. However, this process doesn’t provide a precise overview.

4.7 Applying Statistical Analysis

This part aimed to investigate the similarities and differences in vegetation indices between those four. A statistical analysis was conducted to explore the relationships between weather patterns, vegetation indices, and vineyard yields. Since R studio and Python have their advantages to use for statistical analysis, both of them are used for the analysis of this research. The first step of this methodology was analyzing vegetation indices’ summary of each vineyard region and visualizing them as well as visualizing time series. Visual representation was crucial which made it easier to spot patterns, trends, and outliers throughout the locations and study periods. The second stage was investigating the connections between the vegetation indicators of the vineyard which were NDVI, SAVI, MSAVI, and NDWI. The main aim was to find possible connections between these indicators, which are connected to vine growth, health, and general vineyard performance. To measure the linear correlations between pairs of vegetation indicators throughout the vineyards, Pearson correlation coefficients were calculated. This statistical metric helps in determining the strength and direction (closer to 1 is positive, closer to -1 is negative).

Additionally, an analysis of variance (ANOVA) is run to look for any statistically significant variations between vineyards for every environmental indices. After a significant result was found in the ANOVA, multiple pairwise comparisons were controlled to find out which particular pairings of vineyards' mean index values differed significantly. Increasing the number of pairwise comparisons raises the likelihood that a result may incorrectly reject the null hypothesis. Tukey's test modifies the significance threshold to account for this (Tukey, J. W., 1949). Tukey's HSD uses range distribution (q-distribution) in place of comparing the mean differences to a standard t-distribution as you would in a basic t-test. Because more comparisons lead to more uncertainty, this distribution is wider than the t-distribution.

5. Results

5.1 Topographical Characteristics of the Selected Vineyards

GIS enables us to create topographical featured maps. ArcGIS Pro has been used to create hillshade maps (Appendix 1). Based on those maps, it can be observed that Canalones hillshade includes light and dark areas which can represent a terrain that has ridges and valleys. However, for Chateau, varying shades may provide different slope directions. Hillshade for Cafayeta clearly shows the difference in shading across the image indicating a diverse terrain with flat areas and more hilly sections. On the other hand, Tenuta San Guido shows an orderly pattern, which may indicate agricultural activity that can even be vineyards. Based on each hillshade images, it is hard to say that those vineyard regions share the same topographical features.

To be able to observe terrain features even more, slope maps (Appendix 2) can be checked. Canalones is a clearly defined area on a rather level landscape. It is around more diversified hills. On the other hand, Cafayeta is situated in an area characterized by noticeable elevation variations and severe terrain, which can be challenging for agriculture and might require more work. Canelones and Tenuta San Guido are greater in flat to moderate slopes. It can be ideal for grape maintenance. Whereas, Cafayate has steeper, more challenging terrain. Tenuta San Guido has terracing-like patterns, in contrast to Chateau's more naturally varied slopes and Canelones' rather flat terrain. Lastly, let's take a look at Topographical Position Index (TPI) maps which let us interpret landform features. Based on the map figures (Appendix 3), we can see that vineyards in Tenuta San Guido are located in areas that are either flat terrain or less elevated compared to their surroundings. Despite Tenuta, vineyards in Chateau Bordeaux seem to be located a bit on higher terrain which can be a slope. The area, where Vineyards in Canalones is located, shows positive TPI values. This can mean that vineyards are located on hills or in slightly elevated areas. Cafayate shows the greater value range. Vineyards there seem to be located on a hillside or in an elevated area. Now let's take a look at watershed maps (Appendix 4). We can get an idea about how topography affects the waterflow. Each vineyard is located inside a particular watershed, which affects how water is managed. External hydrological phenomena can impact more when the watershed area with the vineyard is larger. Stream networks close to or within vineyards can indicate where erosion control measures may be needed. The chateau seems to have the highest stream density. It suggests a possibility for adequate water availability and a risk of erosion. Cafayate and Tenuta San Guido have intermediate stream densities and Canelones has the lowest density, which shows less water availability for the vines.

5.2 Analyzing Climate Conditions

Maximum, mean, and minimum temperatures and precipitation values for each vineyard from 2020-2022 (March-Nov) are visualized by graphs. General weather trends of vineyard locations are below.

Cafayeta:

The region has a distinct seasonal temperature pattern, with higher temperatures in the months leading up to March and a progressive cooling off until July, followed by a rising tendency that peaks around November. This typical bell-shaped graph of temperature variance remains stable across time with mean temperatures falling in the winter months (June, and July) and rising in the summer months. Precipitation is more variable than temperature, nevertheless a pattern can still be identified. The middle of the year is often dry, especially around June and July, but precipitation increases as the seasons change to warmer times of the year. This could be an annual change that impacts vineyard activities like planting and harvesting. The variability of irrigation shows that water management is very important for the Lafayette region.

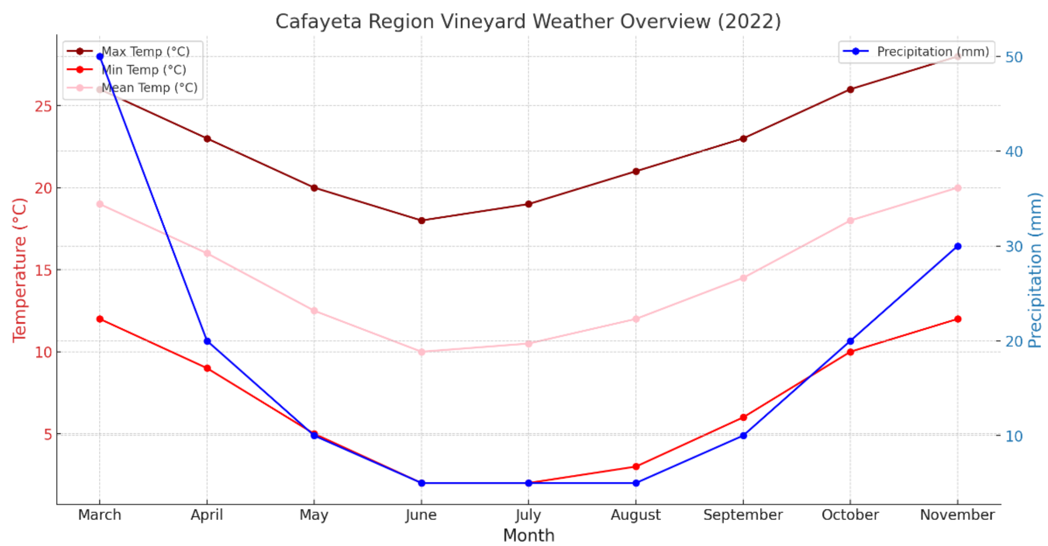

Figure 5: 2022 Weather overview Cafayeta

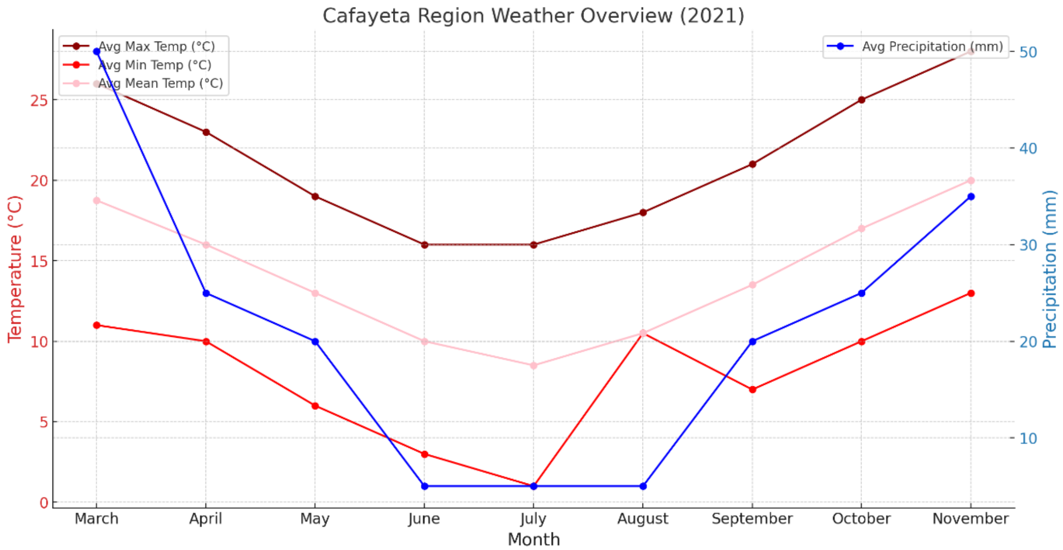

Figure 6: 2021 Weather overview Cafayeta

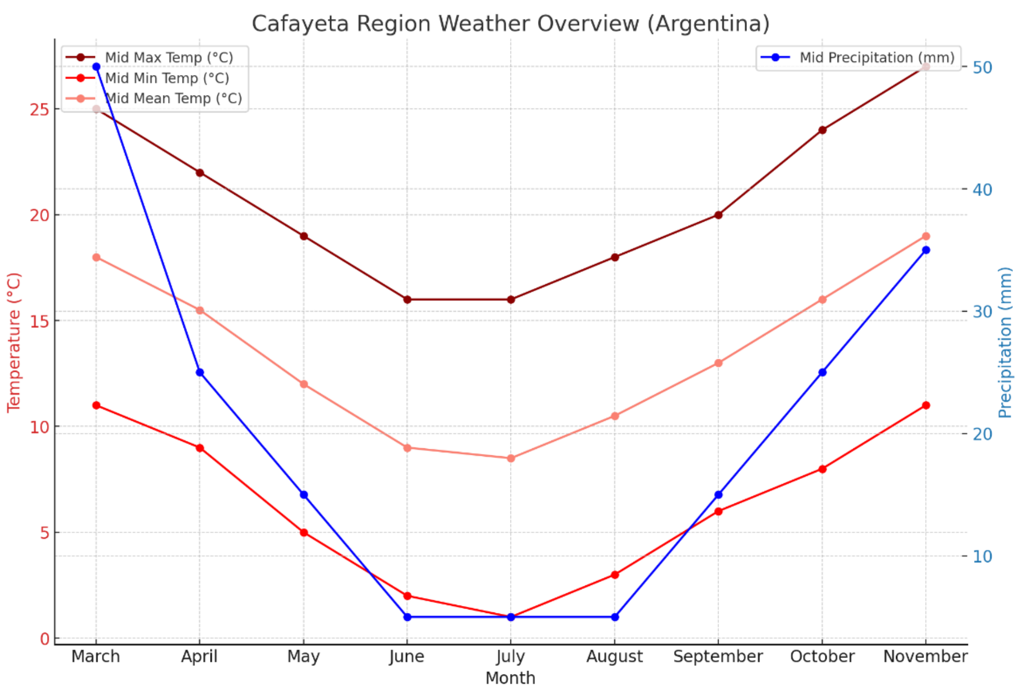

Figure 7: 2020 Weather overview Cafayeta

Canalones:

Changes in temperatures follow a predictable pattern each year, which corresponds to seasonal shifts. Temperatures peak in March, drop to their lowest point in June or July, and then rise again by November. The temperature difference between maximum and minimum temperatures looks to be rather large, which could impact the diurnal range which might be a crucial factor for quality wine production. Precipitation patterns indicate a drier winter with a more wet spring and summer. Precipitation fluctuation also recommends that vineyard managers be adjustable and pay close attention to yearly weather changes, utilizing measures to regulate water delivery during drier seasons while protecting against potential disease threats during wetter months.

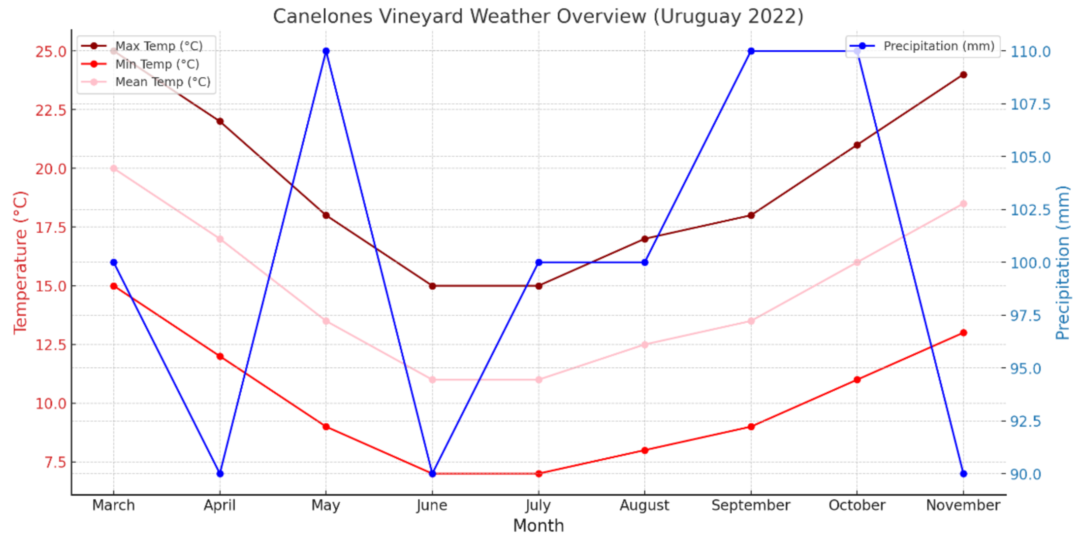

Figure 8: 2022 Weather overview Canalones

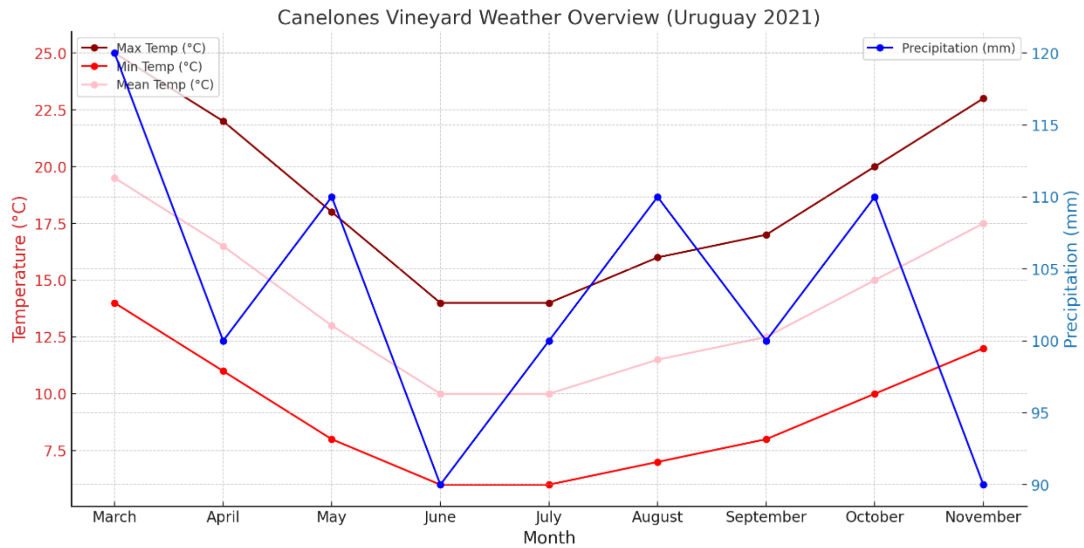

Figure 9: 2021 Weather overview Canalones

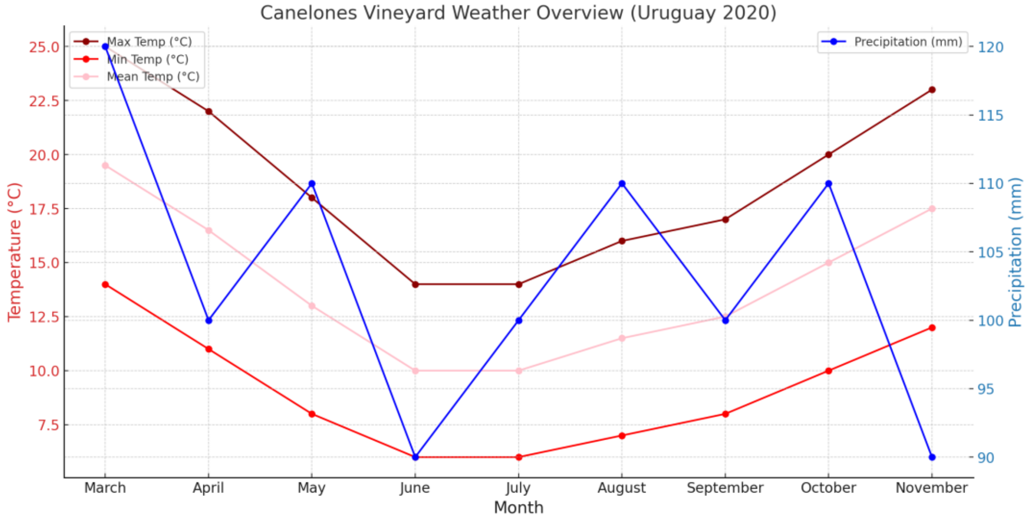

Figure 10: 2020 Weather Overview Canalones

Chateau:

The temperature patterns indicate regular seasonal variation, with higher temperatures in the summer (June through August) and lower temperatures in the winter (November through March). Temperatures consistently climb from spring to summer and fall from summer to winter, making it perfect for vine development. Precipitation is reasonably spread during the years, with a tendency to peak in the autumn months. The Bordeaux region has a moderate environment that allows for grape production throughout the growing season, from bud break to harvest. Although each year presents new obstacles, the region's environment is generally conducive to producing the high-quality grapes that Bordeaux is recognized for.

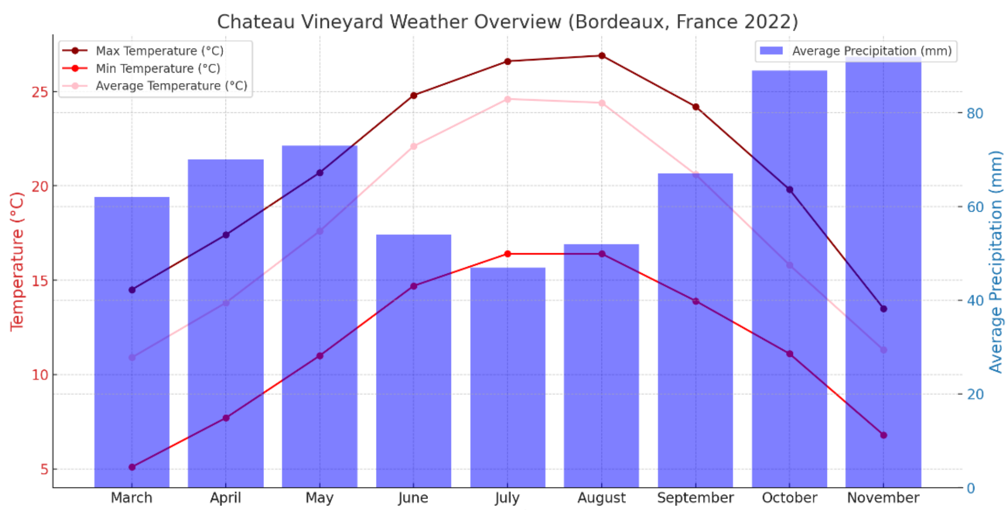

Figure 11: 2022 Weather overview Chateau

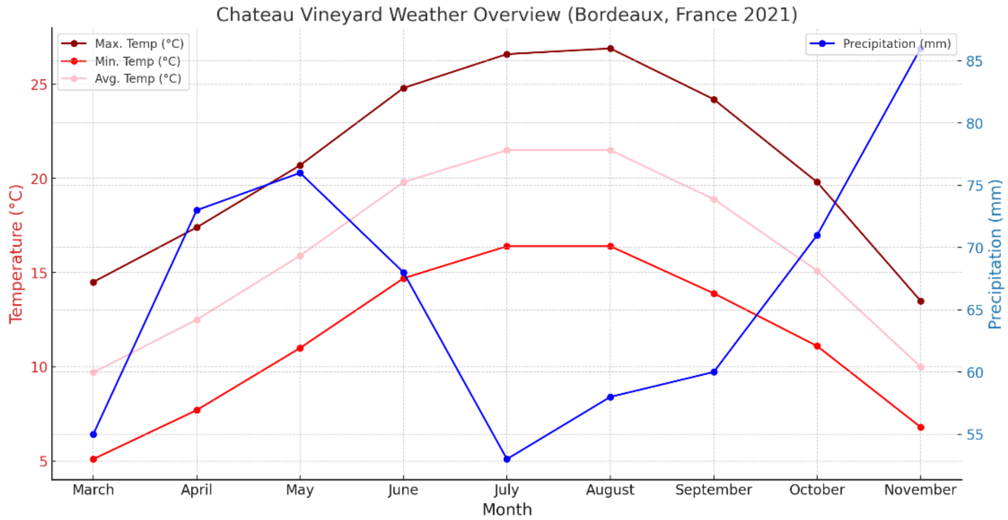

Figure 12: 2021 Weather overview Chateau

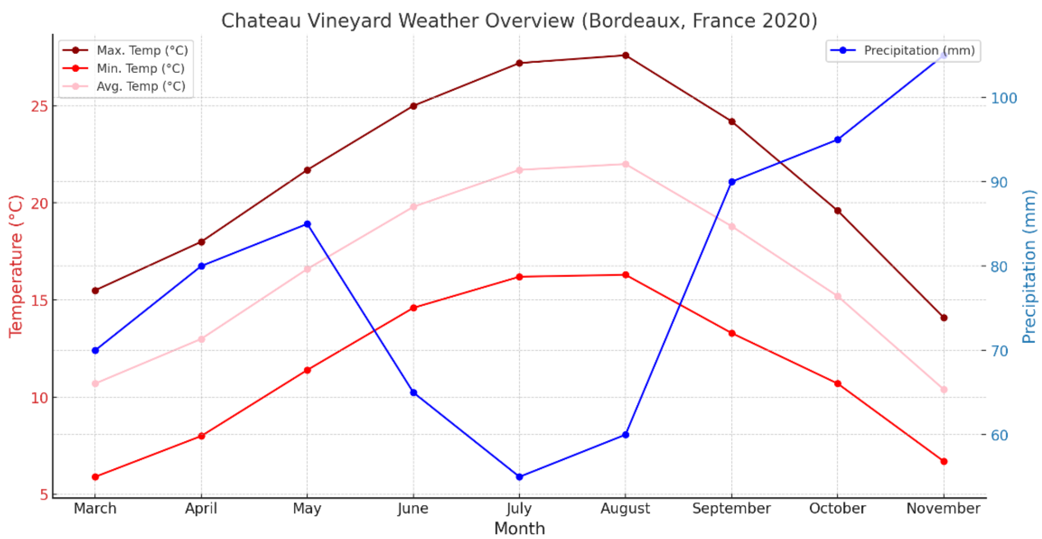

Figure 13: 2020 Weather overview Chateau

Tenuto San Guido:

The temperature profiles follow a seasonal pattern, with peaks in the summer (June to August) and lows in the winter (December to February, inferred from the data). Which is typical of the Mediterranean climate. Precipitation patterns are less foreseeable and vary significantly from year to year, emphasizing the significance of flexible water management and disease monitoring systems in vineyards. The region suggests that it is a favorable area but viticulture management is important as irrigation is important in dry seasons.

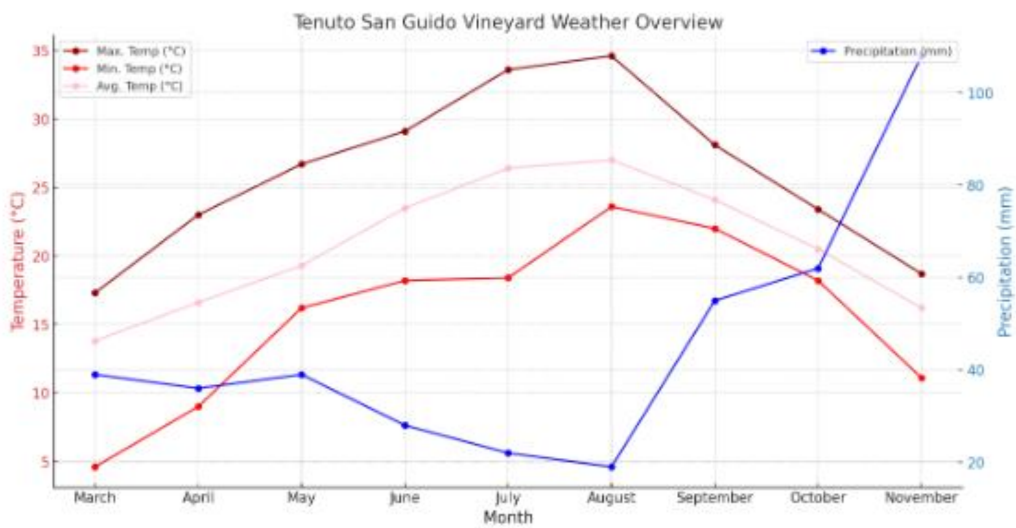

Figure 14: 2022 Weather overview Tenuta San Guido

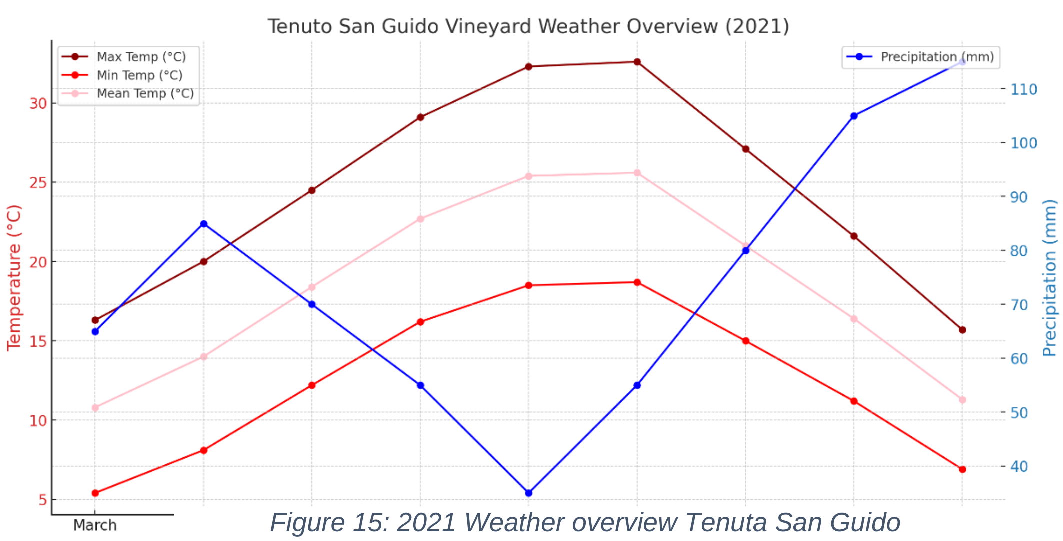

Figure 15: 2021 Weather overview Tenuta San Guido

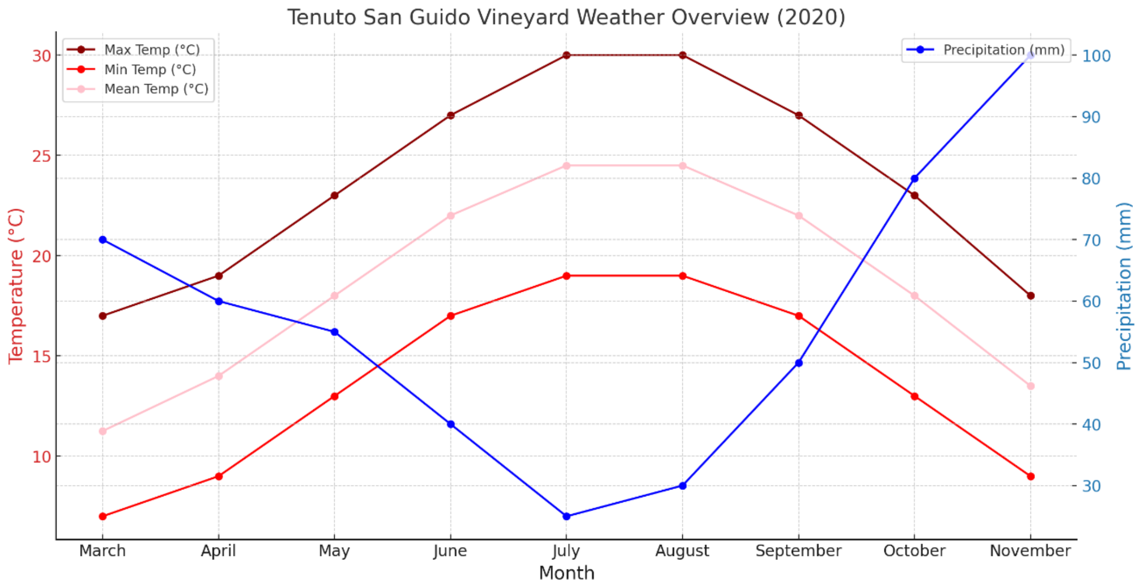

Figure 16: 2020 Weather overview Tenuta San Guido

5.3 Evaluating Vegetation Indices:

RS is a significant tool for us to understand vegetation health. NDVI, MSAVI, SAVI, and NDWI values between 2022 and 2020 are captured from Seninel-2. Those indices are valuable for agricultural purposes. When we check 2the 022 Mean Indices (figure 17), it can be seen that Cafayeta has higher NDVI mean values but the rest of the vineyards have similar mean NDVI values. For SAVI and MSAVI, mean values are quite similar as well for vineyards but Chateau has higher SAVI and MSAVI values this time. According to whisker plots, Cafayeta has a wider NDVI distribution than others. Especially for Canalones and other NDWI variabilities indicate less interquartile status than other vegetation indices.

2021 values (figure 18) show that Canalones is the leading mean NDVI value and Chateau seems the lowest. Besides that Canalones still has the lowest NDWI mean values and Tenuta San Guido has the highest NDWI mean values. Mean values for MSAVI are relatively stable across vineyards. The 2021 Whisker plot shows one more time South American regions have wide ranges for NDVI values. Other vegetation indices show less stable indexes.

2020 values (figure 19) tell us that Cafayate has the highest NDVI mean values besides SAVI and MSAVI values. So it can be said that South American regions are dominating mean values of vegetation indices generally but European Vineyards show higher mean values for NDWI indices.

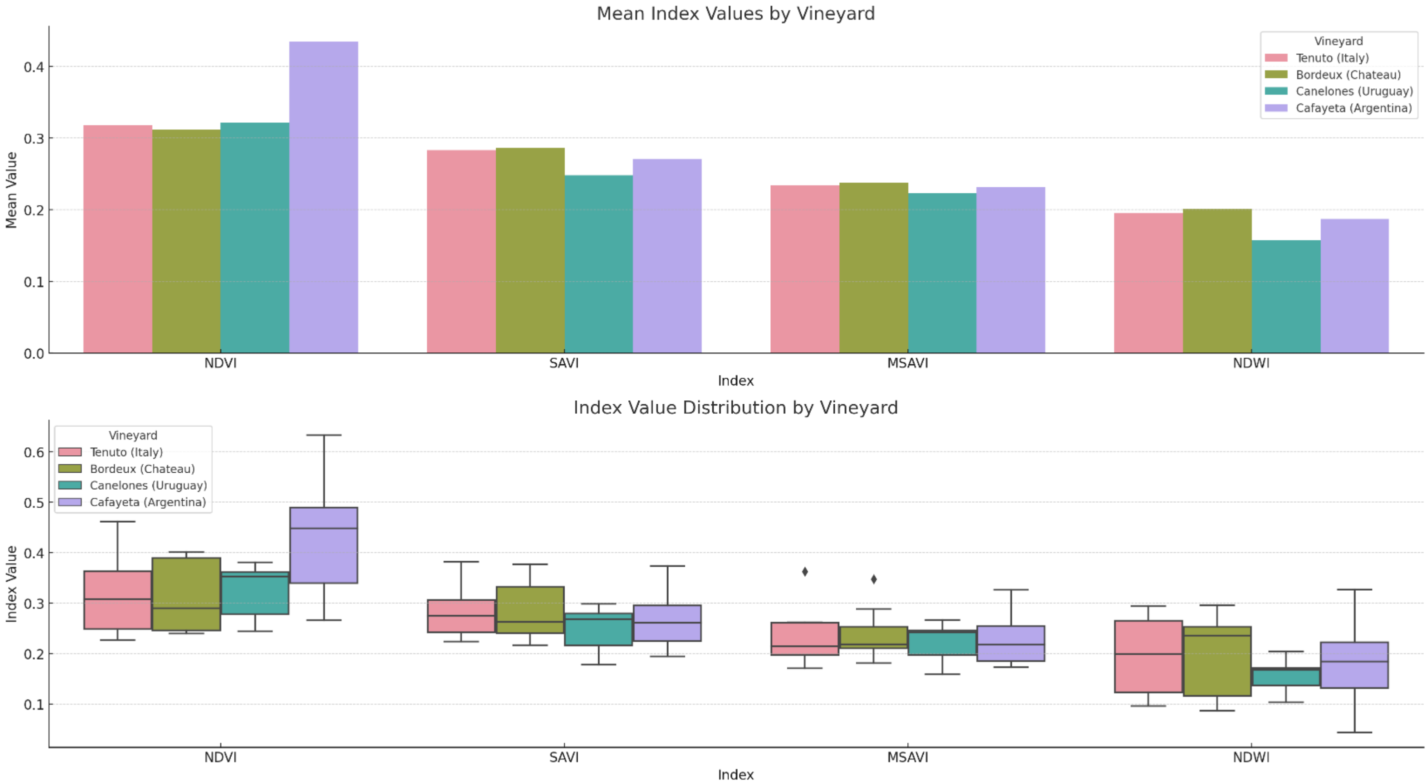

Figure 17: 2022 Mean Vegetation Index Values

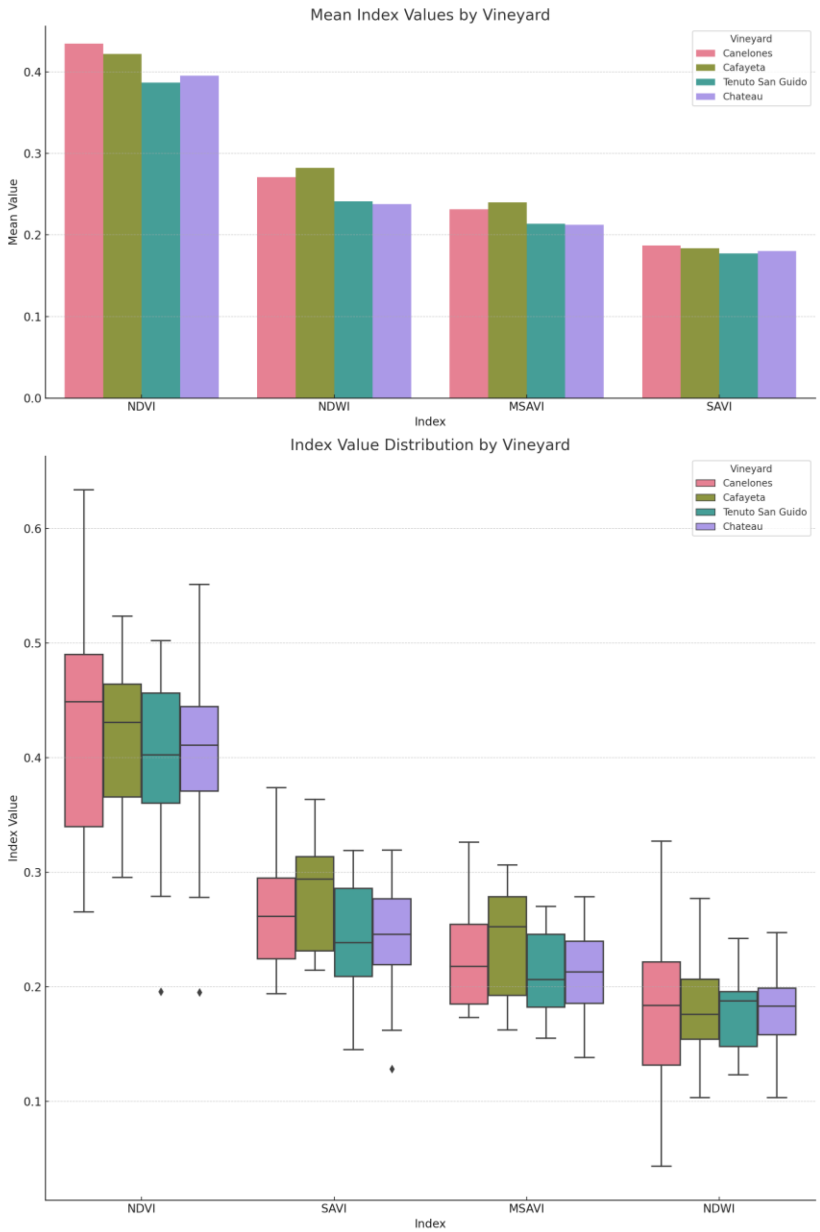

Figure 18 Summary of vineyard indices 2021

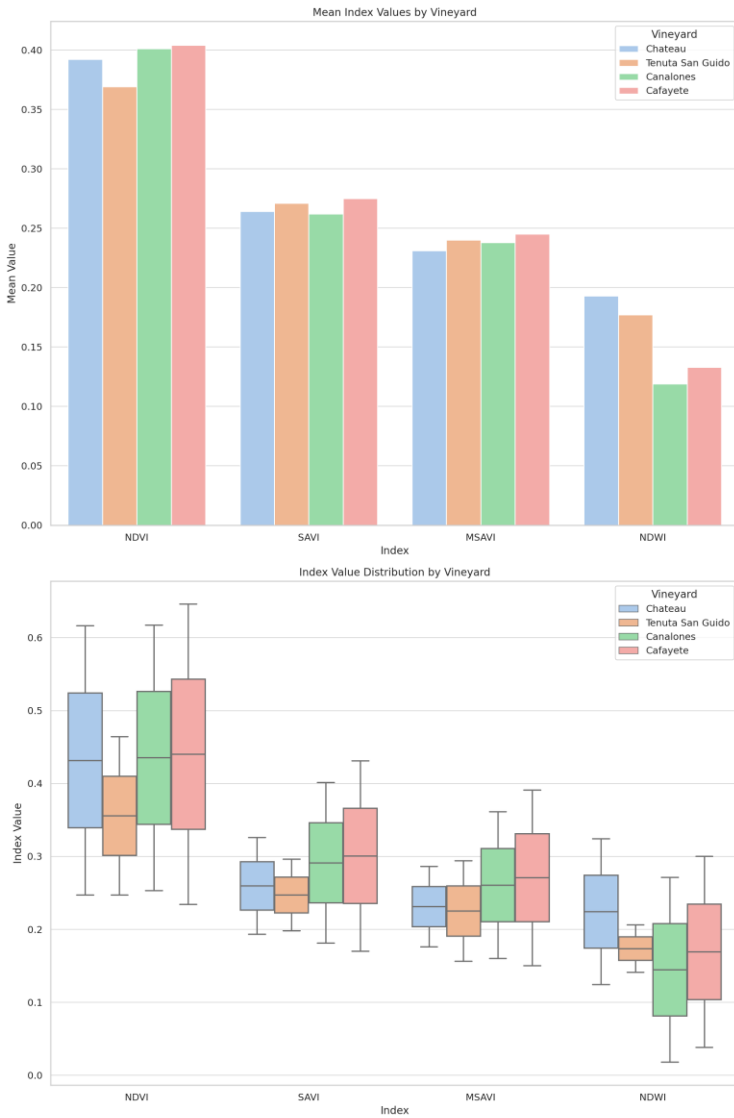

Figure 19: Summary of vineyard indices 2020

The summaries demonstrate that NDVI values differ by region and year, with Argentina (Cafayate) continuously having higher mean NDVI values, indicating strong vegetative growth. The increase in NDVI mean from 2020 to 2022 in Argentina indicates improved vegetation health or better-growing conditions. Bordeaux (Chateau) and Tenuta have moderate NDVI values with some slight changes, indicating relatively constant but changing vegetative health over time. The mean values for SAVI and MSAVI across geographies and years are often lower than NDVI, as expected given the adjustment for soil background. The steady readings in regions such as Uruguay (Canelones) indicate a stable vegetation cover with little year-to-year change.

Argentina (Cafayete) indicates a significant decline in the SAVI mean from 2021 to 2022, which could imply changes in soil cover. The diversity in NDWI across areas and years indicates changes in water stress or irrigation techniques. Uruguay (Canelones) has much lower NDWI values, indicating potential water stress or reduced water availability for vines compared to other regions.

The range and standard deviation of NDWI readings in 2022, particularly in Argentina (Cafayete), indicate surprisingly significant variability in water content within vineyards, which could be attributed to irrigation techniques as it is a very dry region.

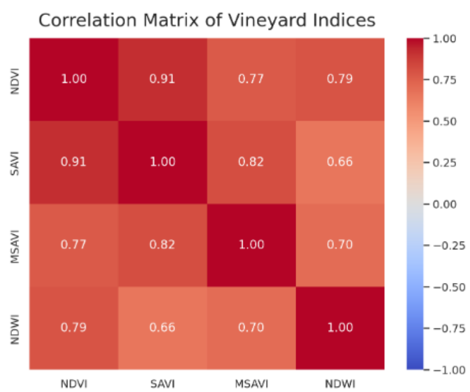

Figure 20: Correlation Chateau

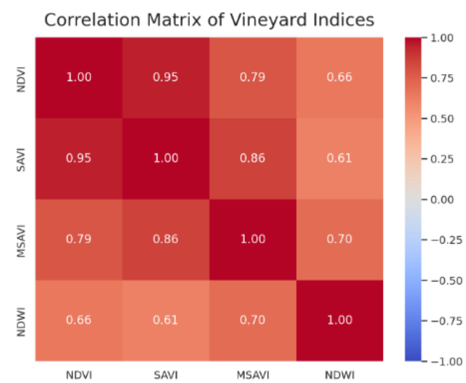

Figure 21: Correlation Tenuta San Guido

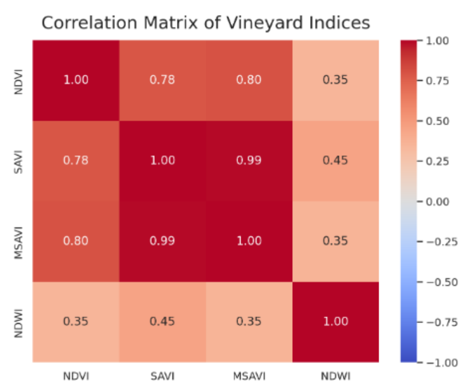

Figure 22: Correlation Canalones

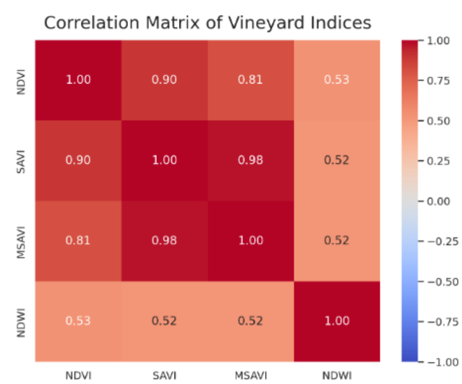

Figure 23: Correlation Cafayeta

The above correlation figures show that there is a strong connection between each vegetation index. However, this connection is weaker in South American regions than in European regions. Which can be caused by especially soil features. Now, it is time to take a look at whether those vineyard indices are similar to each other during the years. To see this ANOVA test is applied and the results are below,

- NDVI: There is a statistically significant difference between the vineyards (F = 3.744, p = 0.022).
- SAVI: There is no statistically significant difference between the vineyards (F = 0.831, p = 0.488).
- MSAVI: There is no statistically significant difference between the vineyards (F = 0.130, p = 0.941).
- NDWI: There is no statistically significant difference between the vineyards (F = 0.568, p = 0.641).

As there is a significant difference in NDVI between vineyards, Tukey's HSD post-hoc test is done for this index to see which specific pairings of vineyards differ. There is a statistically significant difference in NDVI between Cafayeta and Chateau (mean difference = -0.1233, p = 0.0382).

6. Discussion

The first thing to point out is whether Senitnel-2 is efficient for viticulture management. Sentinel-2 provides high-resolution images. One of the most important parts of it is that it includes NIR bands which help us to measure vegetation indices of agriculture. Johnson et al. (2012) also mention about advantages of Sentinel-2 imagery. However, another approach can always be used for vegetation monitoring. Mazzetto et al. (2010). used analog sensors and Sassu et al. (2021) used UAVs for their studies. Both of these methods were useful and provided very detailed results for their studies. Using RS technologies directly in the field can be more efficient. As well as the advantages of Santinel-2. Other natural challenge, such as atmospheric conditions, drought, and heat waves, cannot be ignored. RS and GIS technologies obviously can bring many solutions to these disadvantages for analysis. However, ethical questions can appear while detecting satellite images of vineyards without the permission of landowners. This study doesn't investigate pest management in studied vineyards areas. General Viticulture" by A.J. Winkler points out importance of the pest management in vineyards to protect the quality of grapes. Without knowing what kind of pest management is applied, limits us from enhancing our conclusion about vegetation indices. For example, South American vineyards show healthier vegetation in this thesis however we don't know if pest management effects were studied in European vineyards. It is hard to find the main responsible effect for vegetation health.

It might be better to use more precise RS technology such as field sensors and UAVs to detect vegetation health/monitor vineyards. This study investigates study sites between 2020-2022. Results are quite stable between those years but when only three years are added into research, it can increase limitations for us to understand general statistical patterns of the climate. It may be difficult to make specific comments about the vineyard's characteristics. Previous researches explain the role of topography in viticulture. For example, studies by Johnson et al. (2012) and Sapaev et al. (2023**)** have shown that slope and aspect can affect microclimate conditions, soil drainage, and sun exposure. Those factors play a role in the weather pattern of the areas. Fraga et al. (2012) show the importance of weather patterns in vineyards. With all those different topographical and climate features, vineyard owners should adopt characteristic vineyard management. For instance, more irrigation support may be needed for arid places -Cafayeta vineyard location in our research. On the other hand, erosion management plays a crucial role in vineyards which have more natural water. It is the Chateau region in our case.

The interesting thing that can be observed from this research is that the Cafayeta vineyard region shows the highest NDWI values. That could be the reason for applying more irrigation by viticulture managers than in other studied areas. Viticulture stages such as growing, bud break, and harvest have not been separately analyzed. The mean value of indices was taken between March-Nov which overlays viticulture stages for two different hemispheres. As the winter season (Dec-Jan-Feb) is not included, stats of South American vineyards might be impacted. Including these months might have changed the mean value of vegetation indices. These seasons unfortunately couldn't be used because of that it would prolong the data processing and huge data size would be captured.

There is a high correlation between NDVI, SAVI, and MSAVI in Europe despite their methodological differences and unique adjustments for soil background. However, South American vineyards have a less strong correlation. This might be caused by to soil effect.

Nevertheless, correlation might show all those indices are reliable and constant for identifying vigor health. Studies by Rondeaux et al. (1996) and Qi et al.(1994) highlighted that SAVI and MSAVI are effective tools for accurately assessing vegetation vigor by effectively reducing the impact of soil background reflectance. With these insights, it is understandable that NDVI, SAVI, and MSAVI are highly correlated to each other. However, the soil adjustment value for SAVI is considered as 0.5 for this research which is a standard value as not having enough knowledge – analysis about soil features of study areas. This value can significantly change actual precise values for these results. On the other hand, all those vineyards show good vigor health based on vegetation analysis. The warm seasons are longer in South America. That can cause better vigor health and high indices values. However, weather datasets for vineyard regions are not hundred percent precise either. Because of not having all the needed statistical information, some season patterns are estimated from average weather patterns in study areas and neighboring cities. Another thing we can ask is that South American wineries might be using more advanced technologies for their vineyards. South American vineyards are newer than European ones because of European migration to South America. Europeans might found those vineyard areas in better places and apply their knowledge from their experiences throughout the years of practicing. So South American vineyards tend to show better results.

7. Conclusions

RS and Geographic Information Systems GIS have contributed to this thesis significantly and have helped to analyze and contrast the grape landscapes of Europe and South America. Spatial patterns and environmental factors influencing viticulture in these two areas are captured and analyzed with those technologies. Vineyard landscapes, topographical, climatic, and vegetation features enable us to have an idea about the region. Thanks to spatial analysis and topographical analysis, we can interpret the viticulture practices of the vineyards without being present in those regions. Based on the results of this thesis, South American vineyards show better results regarding to vegetation indices. This result shows that vigor is healthier in South American vineyard sites. This index shows us that climate change and traditional viticulture applications might cause European vineyards to perform less than South America. Vegetation indices show a great correlation with each other across the studied vineyard areas. NDVI, SAVI, and MSAVI are strongly correlated in both European and South American vineyards. NDWI shows a strong correlation with other vegetation indices in the European vineyards but it shows a lower correlation in the South American vineyard sites. That could be the reason for irrigation practices or even the quality of water. Weather in South America is always moderately warm during the year. This might play an effective role in increasing vegetation health. These vegetation indices can be used for monitoring and understanding vineyard health and productivity effectively. Based on ANOVA test results, NDVI discriminates the vegetation health or biomass between other vineyard areas. However, other indices don't show any significant differences. MSAVI and SAVI may be the same due to similar soil moisture conditions and vegetation cover management practices across the areas. Cafayeta and Chateau are causing this significant difference in NDVI value. This might be caused by, vineyard management practices, grape variety, and weather patterns. Weather patterns seem mostly constant – and predictable based on weather stats between 2020 and 2022. As it is observed, there are slight changes in weather stats for each vineyard site. As South America has moderate and warm weather in general, vegetation is healthier than European sites. European weather has colder periods. This might cause grapevines to be less healthy. All four vineyards are located in not the same topographical features. This might show that viticulture doesn't have to happen in the same topographical locations. However, three out of the vineyards are located on elevated terrains. Nevertheless, elevation is different between those vineyards – vineyards are likely to be planned in elevated areas. This thesis contributes to how GIS and RS can be important for viticulture. A comprehended overview of vineyards and an estimation of viticulture practices can be concluded easily. However, more researches are needed to identify more characteristic features of European and South American Vineyards. Tough, RS, and GIS can be cost-saving tools for analysis – as no need to be present in the study area- study site examinations could be useful as well. That can give first-hand observations and spatial data might be correlated easier. Water flows pass through Canelones vineyards less than the other vineyard areas. We can see from the summary graphs that Canalones vineyard area has less NDWI values than the rest as well. This tells us that watersheds and water flow are important for the moisture index of the vegetation.

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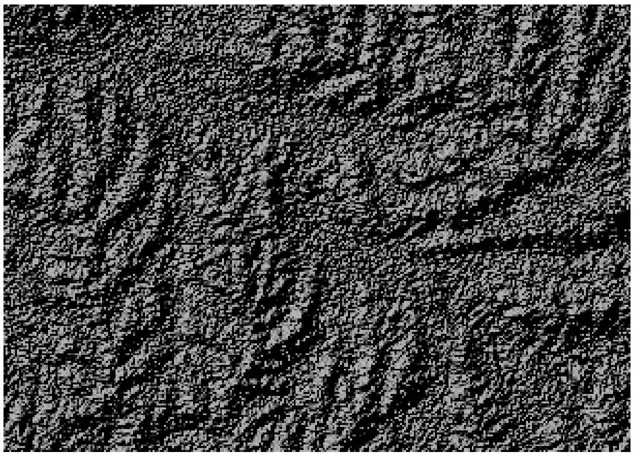
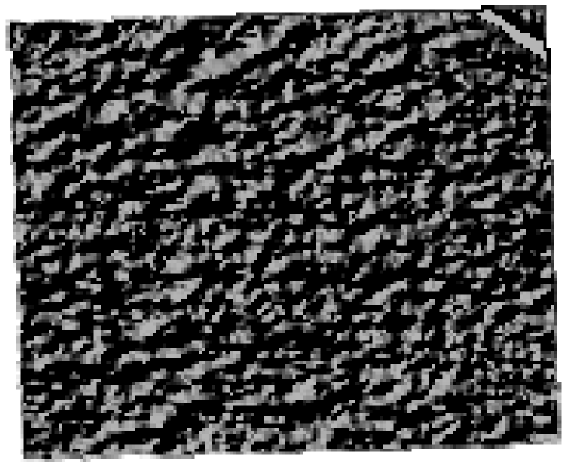
Appendix

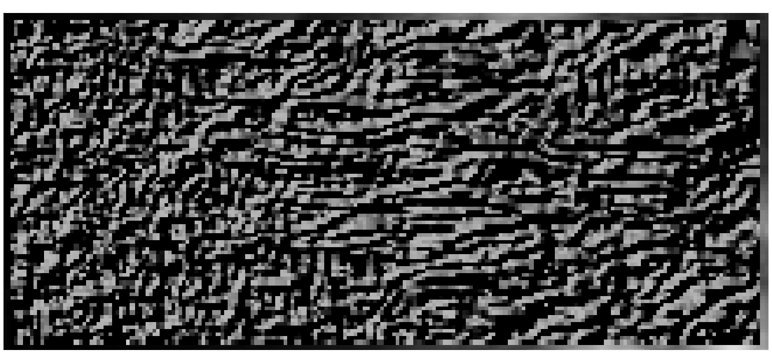
Appendix 1: Hilshade Maps of Study Sites



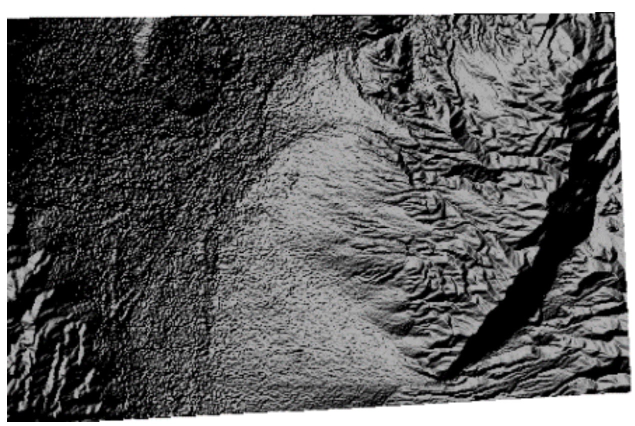
Canelones



Chateau



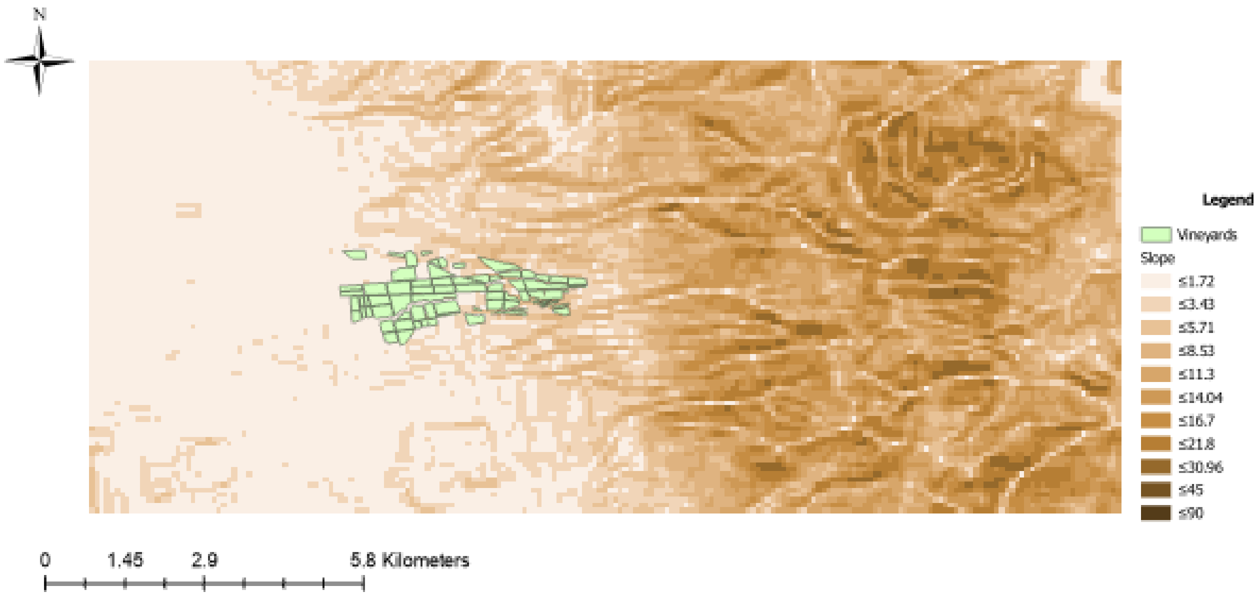
Tenuta San Guido



Cafayate

Appendix 2: Slope Maps of Study Sites

Tenuta San Guido Slope Map



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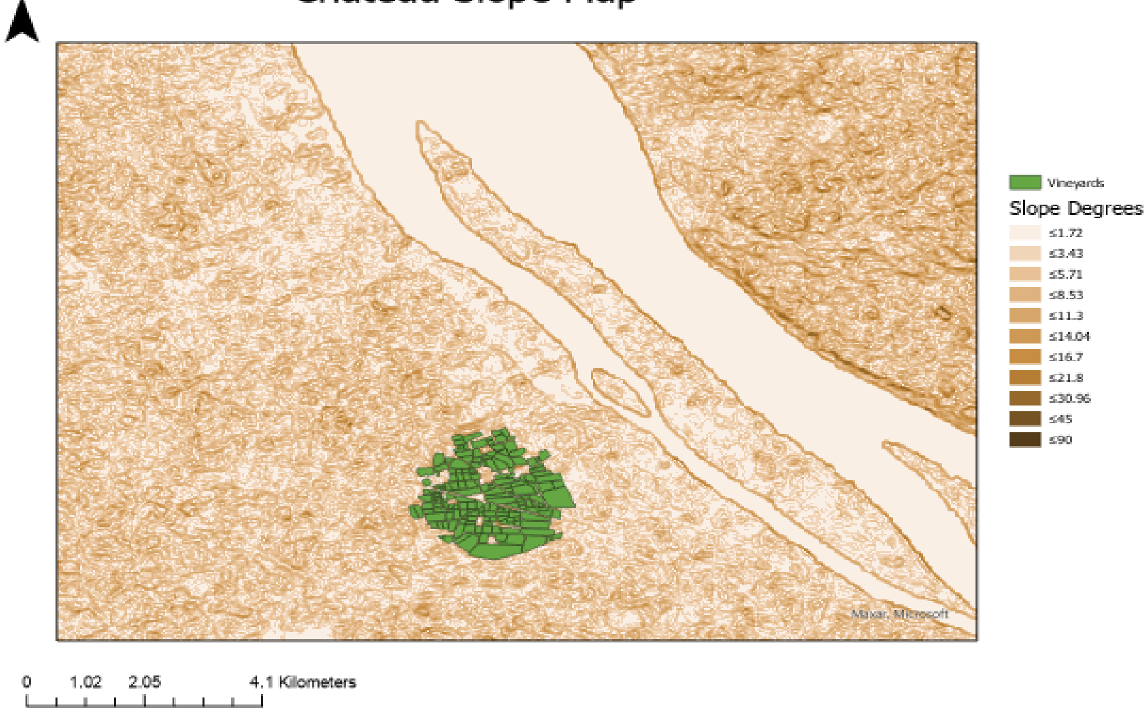

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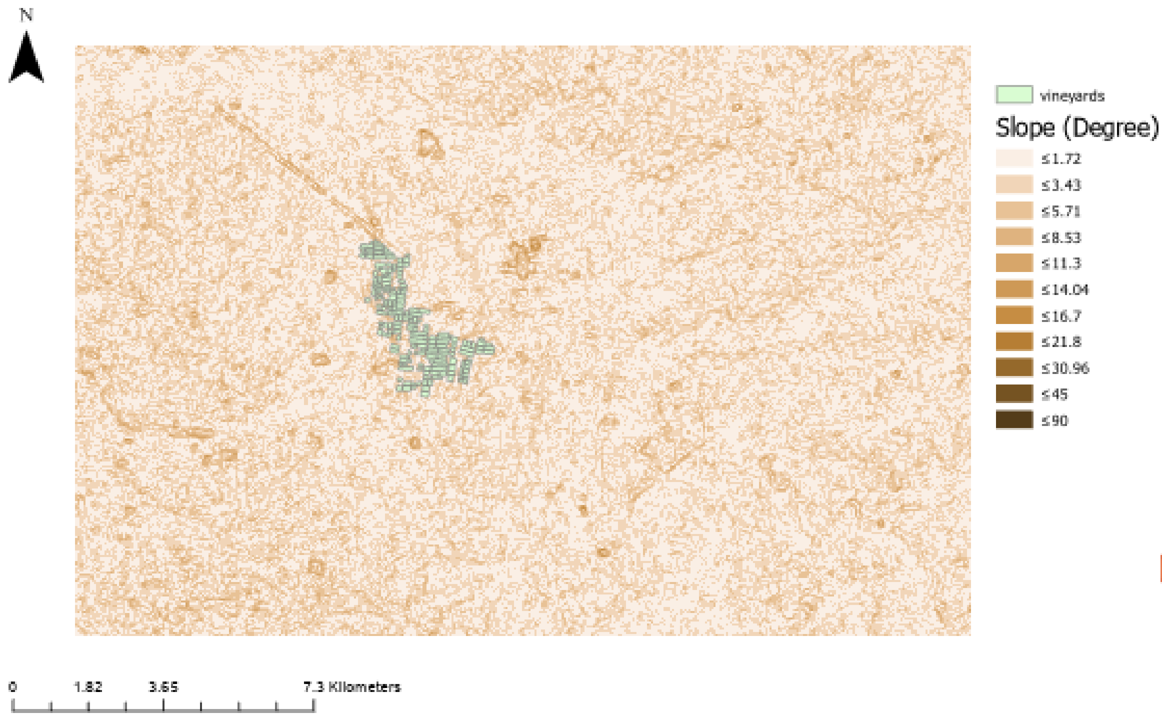
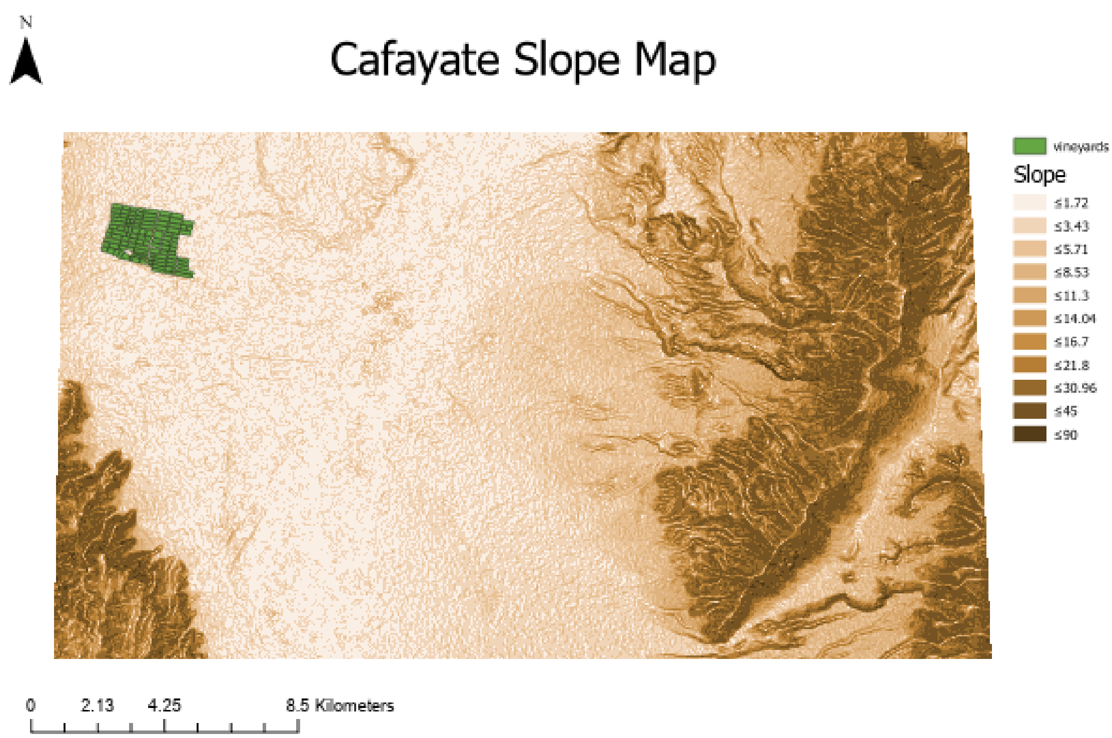
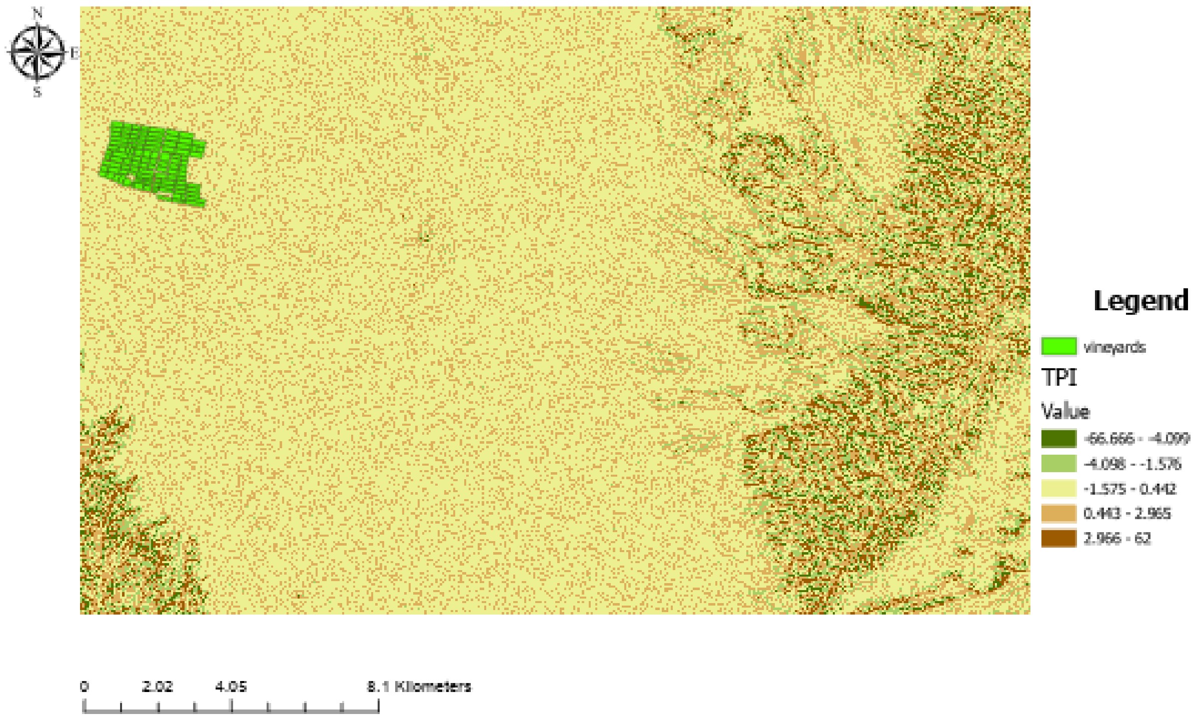


Cafayate Slope Map



Appendix 3: TPI Maps of Study Sites



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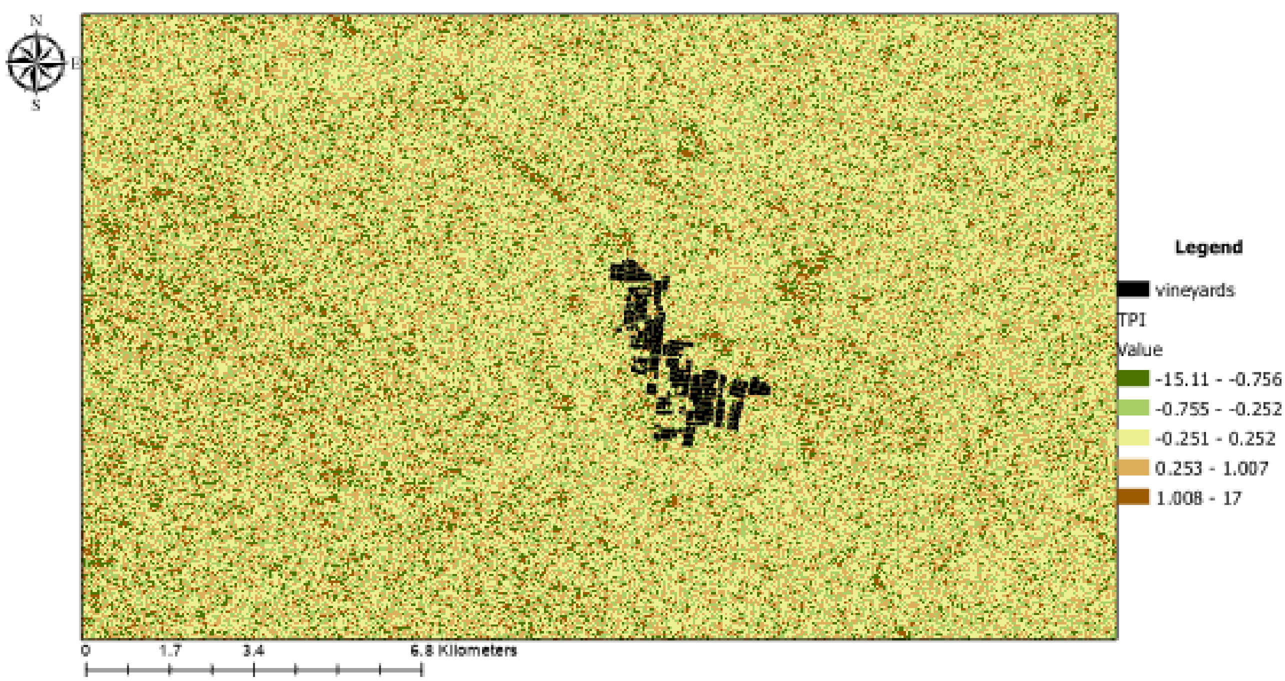

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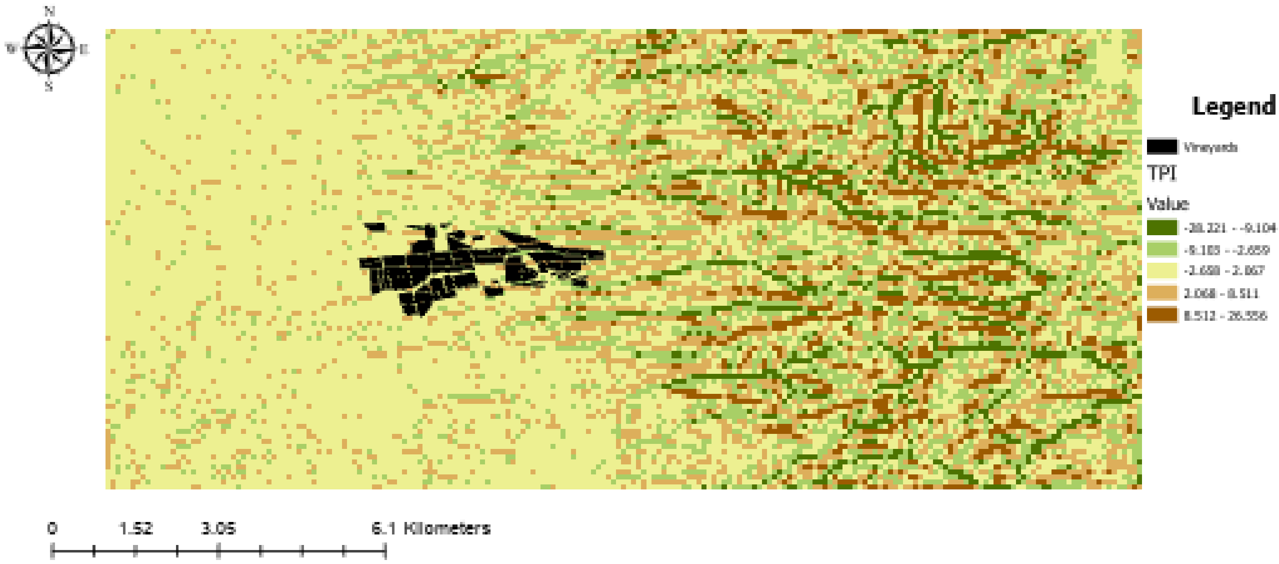

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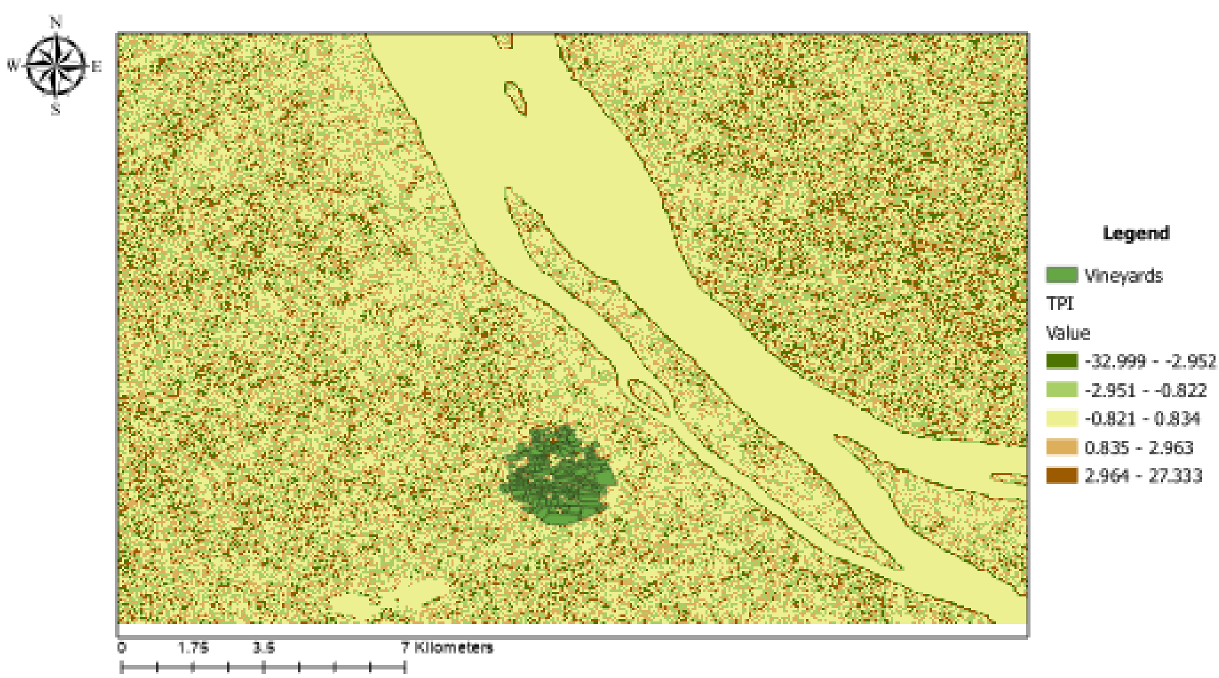
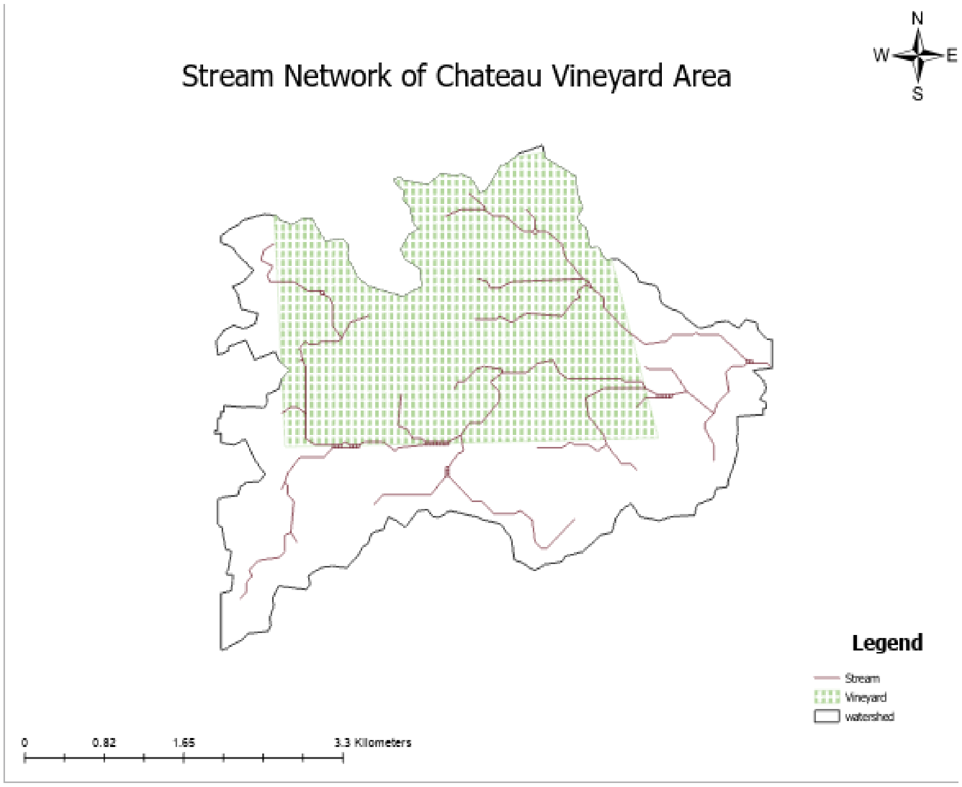
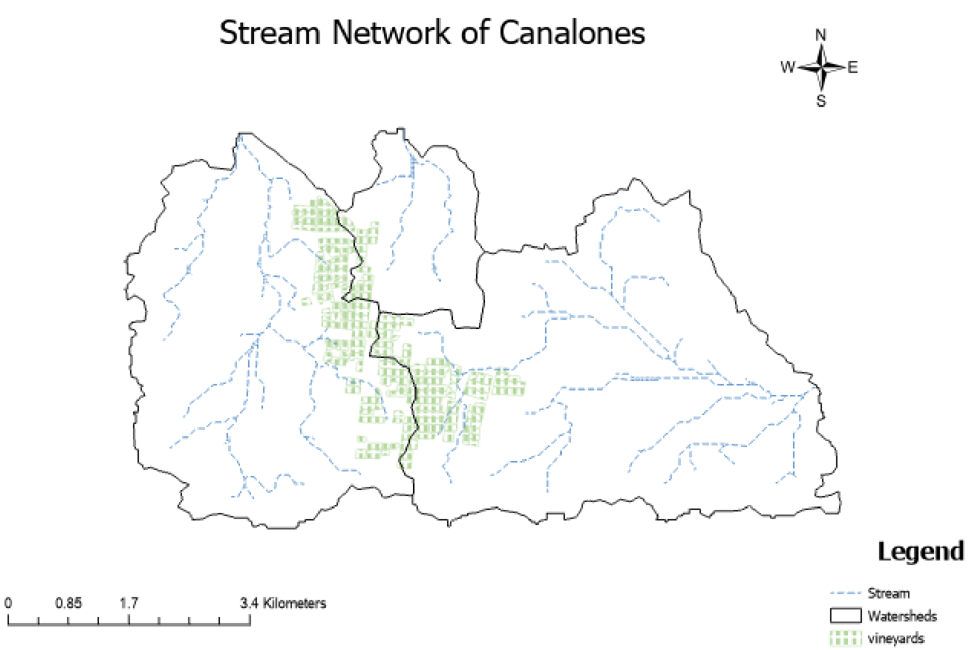
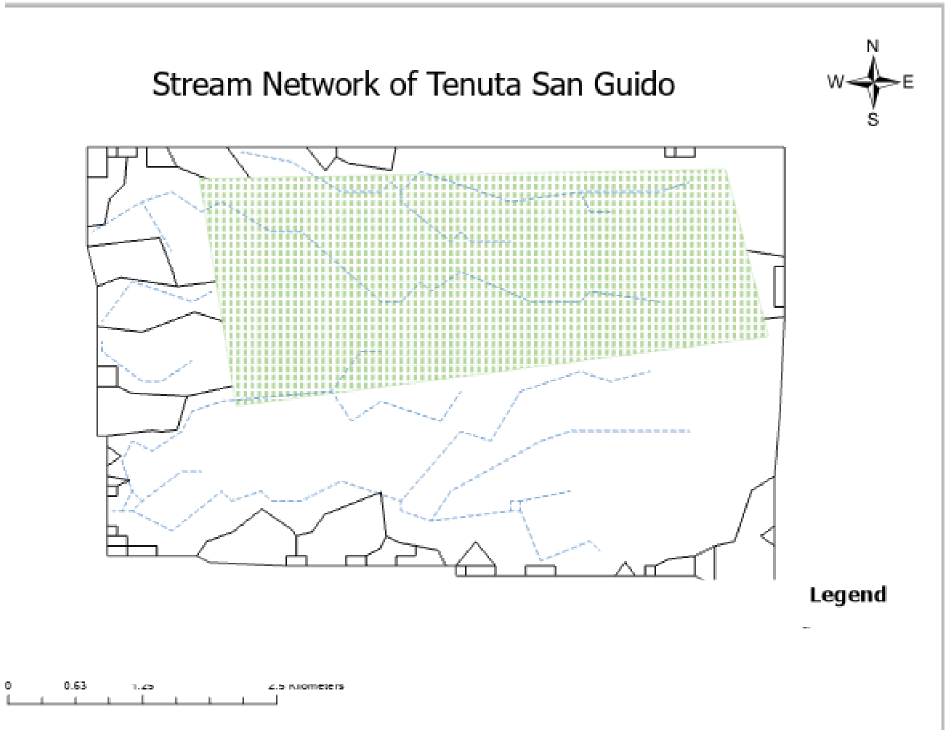


Appendix 4: Stream Network Maps of Study Sites



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E
S
Legend
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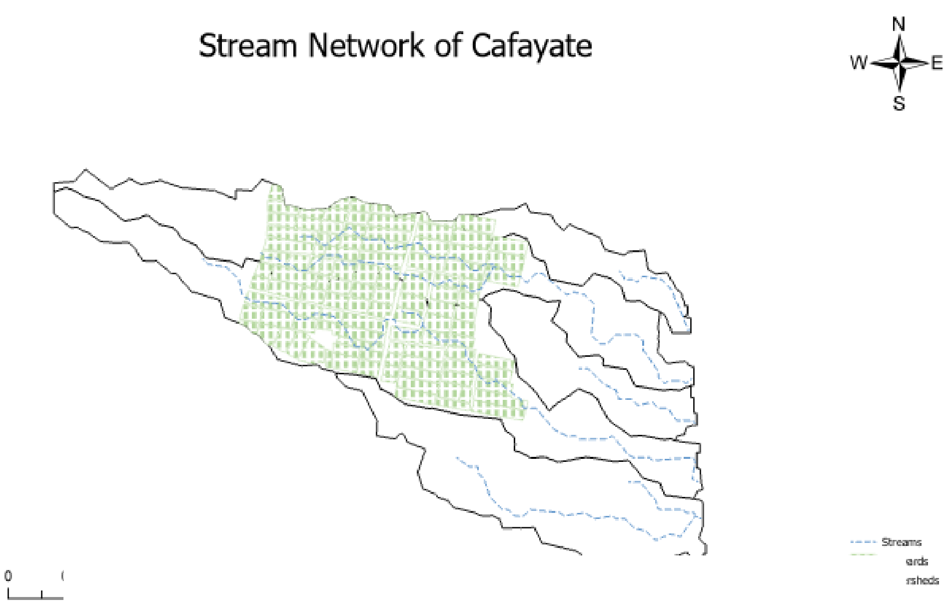
2.5 Kilometers


Stream Network of Cafayate
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W
E
S
Streams
0