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Modeling the Influence of Climate Instability on Agricultural Yields in the Roman Empire

Marthe Deij

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<u>Supervisors</u>:

Kirsten de Beurs
Ep Heuvelink (Horticulture and Product Physiology)
External advisor: Kyle Harper (University of Oklahoma)

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Preface

I am profoundly thankful to my amazing supervisor Kirsten de Beurs. Her guidance, support, and insightful feedback have been vital in shaping this thesis. Every week, she has inspired me to push the boundaries and extract the maximum value from this project. A big shoutout to my second supervisor, Ep Heuvelink, whose assistance in adapting the wheat and grape parameters and providing invaluable feedback on the process as a whole has been immensely appreciated. Special thanks to Kyle Harper for generously sharing his extensive knowledge on the subject, and for helping navigate the complexities of this project from beginning to end. I am truly grateful for all the help. Furthermore, I owe a tremendous debt of gratitude to my parents for their unwavering support. Lastly, a heartfelt thank you to Mirjam, Susanne, and Jorieke for being my biggest supporters. Thanks to each of you, this project has been an incredibly enjoyable experience!

Abstract

This interdisciplinary study uses crop growth models to understand the impact of climate change on past societies through its effects on agricultural yields, taking Roman Italy as a case study and focusing on *Triticum aestivum*, *Triticum durum*, and *Vitis vinifera* Syrah. Using crop growth models, I simulate yields during the Roman Climatic Optimum (RCO) and explore potential yield ranges for the transitional period, and the Late Antique Little Ice Age (LALIA). Modern climate data is used for simulations, using the LINTUL crop model for wheat and the STICS crop model for grapes.

The study confirms the effectiveness of modern data in modeling crop yields during the RCO. For wheat, the LINTUL model demonstrates varied yields under specific conditions, primarily influenced by precipitation levels. Lower spring temperatures show a modest rise in yields due to the modern data skewing towards even warmer conditions than the RCO. Predicting lower yields in later Roman periods aligns with lower precipitation and temperature. Grape yields, modeled with STICS, highlight temperature as a key determinant. Our method encountered challenges in using simulations based on modern data to understand agricultural yields during the LALIA when temperature ranges were significantly lower than spring temperatures in the modern dataset. One location with modeled grape yields displays less bias towards warmth and shows a strong correlation between temperature and yields. Similar trends are expected in other locations during colder periods. Paleoclimatic data supports the fact that modern data is not representative of the colder and drier periods, emphasizing the need for further research.

Wheat and grapes' vital role in Roman society is emphasized, and the analysis underscores that climate vulnerability could have impacted the lives of both the rich and poor. In conclusion, this interdisciplinary study sheds light on the historical image of climate, enhancing understanding of past agricultural systems. The findings contribute to discussions on societal resilience and vulnerability to climate instability, offering insights into potentially one of the reasons that the Western Roman Empire collapsed.

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1. Introduction

1.1 Background

The Roman Empire, during its peak of territorial reach and prosperity, has remained a source of fascination for people throughout history. Its status as the most wide-reaching pre-industrial state of Europe that spanned multiple centuries and stretched over parts of three continents, from the Black to the Red Sea stretching all the way to the Atlantic Ocean as seen in figure 1 (Tretheway, 2019), highlights its lasting impact (Beard, 2016; Gibbon, 1776/2006). During the centuries that Roman civilization reached its peak geographical boundaries as well as having become the largest and most formidable political and military force of the ancient world (Mark, 2018), a discernible period of warm, humid, and relatively stable climate was evident across the Mediterranean region. Also called the Roman Climate Optimum (RCO), this period was characterized by stable warm weather (Büntgen et al., 2011; Joerin et al., 2006) and increased precipitation in parts of the empire (Bini et al., 2020; Büntgen et al., 2011).

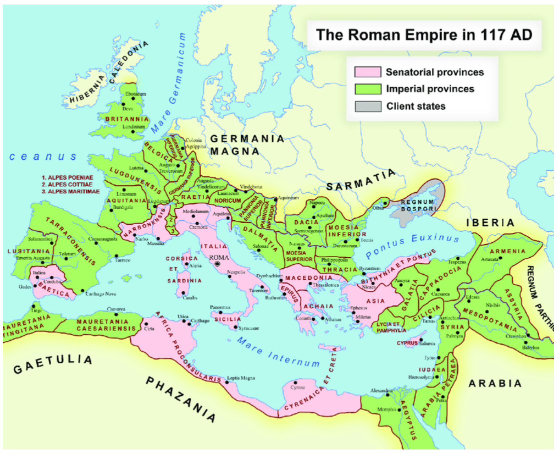

Figure 1: The geographical borders of the Roman Empire in 117 C.E. (Tretheway, 2019).

Furthermore, there was a lack of major volcanic activity that offsets cooling (McCormick et al., 2012). The chronological boundaries of the RCO range from ca. 200 B.C.E. to 150 C.E. (Harper, 2019). However, the climate proved to not always be in the Romans' favor. Starting in the second half of the second century and beyond, the climate shifted away from the warm, humid, and relatively stable conditions that were beneficial for the agricultural society of the Romans. Records of a changing climate can be found in both ancient writings noting the fluctuations in weather patterns (Cyprian, 250 C.E./1996), and paleoclimate reconstructions. For example, solar variability contributed to a period of cooling around the Mediterranean (Steinhilber et al., 2009). Harper (2019) identifies the onset of climate instability and fluctuations as arriving around 150 C.E. and persisting until approximately 450 C.E. This transitional period gave way to the Late Antique Little Ice Age (LALIA), which lasted from approximately 535 C.E. to 700 C.E. (Büntgen et al., 2016; Harper, 2019). This period is characterized by at least three major volcanic eruptions that triggered dramatic temperature decreases. Within a decade after the eruption of an Icelandic volcano in early 536 C.E. (Gibbons, 2018), the temperatures had dropped by a full degree Celsius (Peregrine, 2020). Precipitation was seen to also have plummeted dramatically at the start of the sixth century in central Europe (Büntgen et al., 2011). Furthermore, temperature data retrieved from tree-rings in the Alps show low-temperature anomalies during the LALIA (Büntgen et al., 2016). Thus, the Romans enjoyed favorable climate conditions during the height of the empire, which sharply contrasted with the harsher environmental challenges they faced during the decline and fall of the Western Roman Empire (WRE).

These less favorable climate conditions had their impact on the agricultural society of the Romans. In the second and third centuries, the Roman Empire grappled with growing political, military, and economic difficulties as well as the changing climate conditions. During these times the frequency of lavish harvests noticeably declined in Egypt, the breadbasket of the Empire, while poor harvests became more frequent (McCormick et al., 2012). The end of the RCO is proposed to have increased the unreliability in agricultural yields for the Romans (Tainter & Crumley, 2006). Moreover, preindustrial societies relied heavily on climate conditions as they were vulnerable to famine, often triggered by variations in drought, floods, frost, or wildfires (Büntgen et al., 2011). The later era of the Migration Period in Europe was marked by significant political, social, and economic upheavals. These conditions align closely with climate instability and temperature drops, highlighting the interconnectedness of environmental factors with historical challenges (Büntgen et al., 2011). Scholars attributed the decline of the favorable climate the Romans had once known to the fall of the WRE (Harper, 2019; Hu et al., 2022). However, while the declining climate has been used as an indirect indicator of agricultural failure, the actual crop yields have not yet been modeled. The real effects of climate change on agricultural societies have not yet been fully understood. The improvement of historical climate proxies has heightened the demand for interdisciplinary collaboration in the domains of paleoclimatology, the historical study of climate, and its impacts on societies. The regional effects of climate change, the non-linear effects, and the role of temperature and precipitation remain unclear.

Written records for agricultural output extend only to the recent past. Thus, to explore whether climate change had a substantial influence on declining agricultural output that contributed to the fall of the WRE, we use crop growth models to model crop yields. We focus on grapes and wheat, since wheat and the wine made from grapes were the primary foods on the Roman menu (Killgrove & Tykot, 2013). Crop growth models are very effective for predicting possible impacts of climatic change on crop growth and yield (Sargun & Mohan, 2020). Crop models usually require datasets regarding crop characteristics and management, weather, soil, and often information about diseases and pests (Nonhebel, 1993). By running crop models for ancient wheat and grapes, using simulated Roman weather conditions as input, we simulate yield outcomes for various climatic periods. We run a simple simulation using the LINTUL-2 crop growth model to calculate yield outcomes for landrace spring wheat (Hijmans, 2019). Furthermore, we use the STICS crop growth model to model the yield outcomes for wine grapes, few other models are capable of simulating grapevine systems (Valdes-Gomez et al., 2009). Created in 1999, LINTUL2 is a crop growth model designed for simulating crop development under potential and water-limited conditions. It analyzes crop experiments and initiates crop modeling studies, providing outputs such as biomass production, yield, and soil water content for irrigated and rainfed scenarios (Leffelaar, 2011). STICS, or the Scientific, Technical and Interdisciplinary Simulator of Soil-Crop System Functioning, originated from a collaborative effort in France in 1996. The crop model requires daily data and uses soil, climate, and crop information as input. STICS simulates crop development, growth, yield production, and environmental impacts (Beaudoin et al., 2022). Yield outcomes for the RCO can be compared with yield outcomes in the transitional period and the LALIA. These methodologies require various climate data inputs. By gaining more insights into how agricultural yield was affected by climate change during the peak of the Empire compared to later periods of climate instability, we can gain a better understanding of how past agricultural systems were affected by climate change. Furthermore, by enhancing the understanding of social resilience and vulnerability to climate instability in the past, we expand insights into potential future consequences of climate change and the strategies for adapting to them.

1.2 Research needs

1.2.1 Current research

There are examples of studies that have estimated yields and agricultural productivity during the era of the Roman Empire, however, most papers do not investigate the impact of unfavorable or changing climate conditions.

For example, Dermody et al. (2014), simulated cereal yields under changing climate conditions around the year 200 C.E. using a hydrological model. Their study revealed that, contrary to expectations, increased precipitation negatively impacted rainfed regions' yields due to accompanying temperature decreases and reduced evapotranspiration. Higher temperatures correlated with increased crop yields. It's important to note that this study mainly focused on modeling water availability for crops using a hydrological model, rather than exclusively focusing on crop yields (Dermody et al., 2014).

Others have also studied the expansion of vineyards beyond the Mediterranean region at the time of the RCO (Bernigaud et al. 2021). By modeling wine production for the 6th century B.C.E and the first century B.C.E., a strong influence of climate change on wine production was found. The study identifies favorable conditions for viticulture expansion and found that successful vineyards may have expanded as far as northern Gaul in the RCO but did not focus on the effects of unfavorable climatic conditions on wine production during the decline of the Roman Empire (Bernigaud et al., 2021). Multi-criteria evaluation methodology, instead of crop models, has also been applied to investigate the yield of wheat, olives, and grapes in the Tiber valley from the middle republic era to the early imperial society (Goodchild, 2013). However, while several factors were evaluated in the analysis, including climate, soil quality, vegetation patterns and socio-economic variables, there was not analysis on the impact of changing climate on crop yields.

1.2.2 Research gap

In this thesis we aim to address four important and interrelated research gaps.
First, we have identified a lack of systematic modeling of agricultural yields when comparing the warm and humid Roman Climate Optimum to the less favorable climate conditions during the transitional period and the Late Antique Little Ice Age. The goal is to understand the impact of climate change on agricultural systems, such as Italy, which boasts diverse characteristics, using computer-based crop yield models. And to gain an insight into how much of an influence climate variability has on crop yield.

Second, we tried to address how to model crop yields when a scarcity of historical weather data for the period in question exists. Daily weather data was not measured and recorded, and tools to effectively measure and store this data were not yet invented. However, researchers have constructed paleoclimatic data sources to reconstruct ancient weather patterns. For example, Büntgen et al. (2011) used tree ring data to establish temperature and precipitation records spanning from 400 B.C.E. to 2000 C.E. Additionally, Joerin et al. (2006) identified cold periods during the Holocene by analyzing radiocarbon dates obtained from the recession of Swiss glaciers. Hu et al. (2022) present stalagmite-based climate records for the circum-Mediterranean region from approximately 550 B.C.E. to 950 C.E. Steinhilber et al. (2009) investigated the total solar radiance throughout the Holocene era by analyzing data obtained from ice core samples. Zonneveld et al. present a temperature and precipitation reconstruction for the gulf of Taranto using marine core samples for 200 B.C.E to 600 C.E. (2024). Finally, Wanner et al. (2008) provide an overview of the overall climate fluctuations during the mid to late Holocene period. Their study encompasses cooling events and delves into various paleoclimatic findings gathered from the literature. The research gap regarding this thesis project is comparing modern weather data to paleoclimatic data for the period of the Roman Empire. Both LINTUL and STICS rely on daily weather data (Sargun & Mohan, 2020). If recent weather data can be compared to paleoclimatic data, this recent representative data can be used to gain insights into ancient crop yields. It is important to recognize that modern data does not correspond to Roman historical timescales, yet Roman paleoclimatic data, which is annual at best, lacks the level of detail found in recent records due to the absence of daily data. However, comparing recent weather data to paleoclimatic data can still offer valuable insights into ancient weather patterns, bridging the gap between the requirements of models like LINTUL and STICS and the available historical data.

Third, there is a need to adapt crop yield models, such as LINTUL-2, to account for ancient crop varieties. During Roman times, there were distinct crop variations that must be considered when applying such models. Local wheat landraces have been grown for thousands of years in a Mediterranean climate (Frankin et al., 2021). LINTUL is a simple crop growth simulation model, making it particularly valuable for modeling ancient crops due to its simplicity (Hijmans, 2019). While the model can be customized for landrace wheat, however, it is necessary to adapt the model applicable to historic crops, such as those potentially cultivated by the Romans. This requires sourcing specific data related to landraces of spring wheat that were likely cultivated during Roman times, including information on their light use efficiency. Similarly, it is important to gather information about ancient grape varieties to refine the STICS model. While Roman agricultural writers documented the grape varieties they cultivated, it is currently not possible to directly link these names to modern grape varieties (Ramos-Madrigal et al., 2019).

A fourth research gap is linking the relationship between climate variability and agricultural productivity during the Roman Empire. Given the interest in the effects of climate on ancient Rome (for instance, see 'The Fate of Rome: Climate, disease, and the end of an empire') there is a need to understand in greater detail the dynamics of agriculture. Harper connects paleoclimatic data with the societal situation of the Roman empire. He describes possible connections between climate variability and the effects on agricultural productivity and its possible influence on the fall of the Roman Empire. However, he notes that there is still much more research needed to conclude if this possible phenomenon directly influenced the fall of the WRE (Harper, 2019). Furthermore, there is Hu et al. (2022) who argue that climatic variability could have resulted in the fall of the Roman empire, although they don’t directly link this to agricultural yields. Lo Cascio and Malanima describe the effect of a warmer climate on wheat as well, they argue that one degree of warming increased the altitude threshold for wheat cultivation by 100–200 m in mountainous areas like Italy's Apennines (2005). However, Paul Erdkamp argues that the ups and downs in agricultural production in an area were influenced more by the productivity of seeds and labor there rather than the climate, declaring that it mainly depended on how the land was owned and how peasants used their own household labor to survive (Erdkamp, 2019). The research gap that will be bridged in this project is the modeling of yields for the climate variable periods in the context of the state of the Roman Empire. We will explore the link between agricultural performance and climate variation.

1.3 Research aim and questions

The overall research aim is to get insight into how crop yields of landrace spring wheat and wine grapes were affected by changing climate conditions, specifically the shift from the Roman Climate Optimum to a cooler and more variable climate in the transitional period and later in the Late Antique Little Ice Age. We are specifically interested in crop yields during the transition from the Roman Empire's expansion to its later decline, by examining the impact of climate variability on agricultural productivity in the Roman Empire.

Sub questions:

1. How does daily climate data from 1850 to 2014 for several locations in Italy compare to paleoclimatic records from the Roman Climate Optimum to the Late Antique Little Ice Age in terms of average temperatures and precipitation?

2. What range of potential yield for *Triticum aestivum* and *Triticum durum* can be determined for several locations in Italy, based on the LINTUL-2 crop growth model using climate data from 1850 to 2014 as input, and how do these estimates align with historical climate conditions resembling specific years within the Roman Climate Optimum to the Late Antique Little Ice Age in terms of average temperature and precipitation?

3. What range of potential yield for grape vine *Vitis vinifera* Syrah can be determined, using the STICS soil-plant simulation model, for several locations in Italy, using climate data from 1850 to 2014 as input, and how do these estimates align with historical climate conditions resembling specific years within the Roman Climate Optimum to the Late Antique Little Ice Age in terms of average temperature and precipitation.

2. Data and methods

2.1 Study area

We are interested in the areas of wheat and wine grape growth in Italy in Roman times. Delving into the workings of wheat and wine grape cultivation during Roman times in Italy unveils insights into the complex agricultural state that was the Roman Empire. It should be noted that the Roman Empire was widespread and dynamic. Italy's climate variations were different from other regions in the Empire, and agricultural methods within the Roman Empire varied widely as well. For this study, we selected Italy as the research location due to its historical significance as the birthplace of the Roman Empire and its central role throughout the empire's reign.

2.1.1 Study area description

We chose ten specific study areas in Italy of 5 km by 5 km; five were designated for wheat and five were designated for wine grape growth. To select suitable study areas for implementing the crop models, we used modern maps of wheat cultivation (Marletto, 2009) and wine production areas (Amato, 2007). The reasoning for selecting these areas is that the cultivation of wheat and wine grapes in present-day locations is expected to resemble historical farming sites during the Roman era because areas that were deforested during the height of the Roman Empire correspond to modern-day intensive agricultural regions (Kaplan et al., 2009). To select the study areas, we overlayed the maps with a Digital Elevation Model (DEM) to ensure a range of elevations. The criteria for selecting study areas included variations in geographical features such as north-south orientation, coastal-inland location, valley-upland positioning, and a comparison between Sicily and the mainland. Additionally, to verify that these areas likely had agricultural activity during Roman times, we cross-referenced each location with a map of ancient Roman settlements (Ahlfeldt, 2020). If there was a Roman settlement of any kind nearby, such as towns, forts, or cities, it was likely to have agricultural activity in its vicinity, including smaller farms. Additionally, we checked if there were nearby settlements in the form of larger agricultural estates known as 'Latifundia' that owned more than 125 hectares of land (Spurr, 2016). A full description of the characteristics of each location can be found in Appendix 1.

2.1.2 Map

Figure 2 shows the study areas.

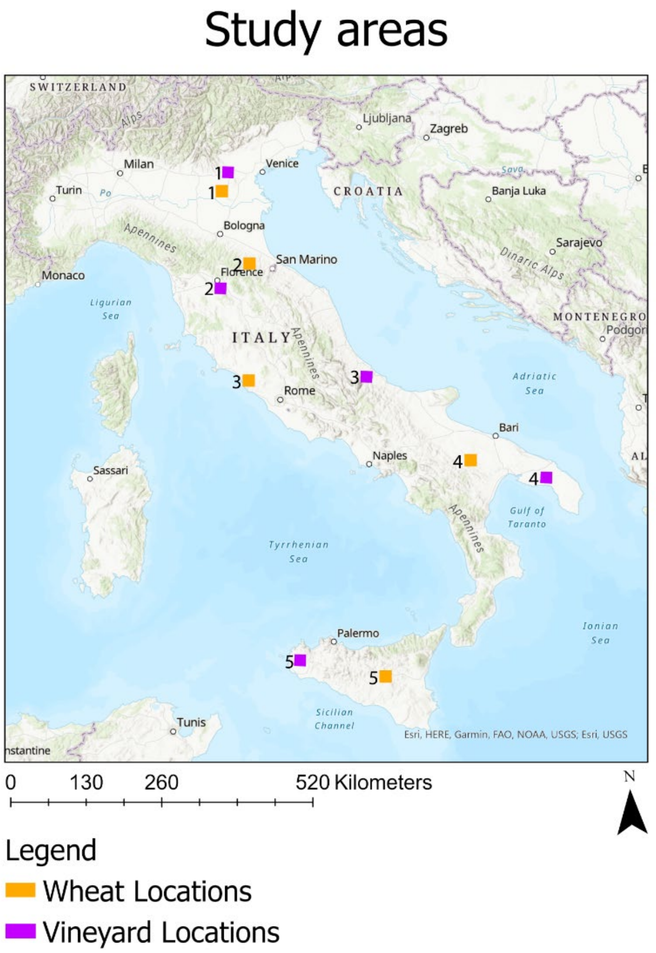

Figure 2: The 10 chosen study areas to model wheat and grapes. Note that the squares are not to scale.

2.2 Datasets
Below we describe the datasets used in two selected crop models: LINTUL and STICS. We also used paleoclimatic data to get a better understanding of the climate during the Roman period. A comprehensive dataset description that outlines the specific datasets used for each research question within the thesis project can be found in Appendix 2.

2.2.1 Paleoclimatic data
To compare recent climate data to paleoclimatic records, we used marine core paleoclimatic data for the Roman period. This dataset contains a temperature and precipitation reconstruction for the years 200 B.C.E. to 600 C.E. for the Gulf of Taranto from a sedimentary archive (Zonneveld et al., 2024). The temperature values are reconstructed based on studying downcore fossil dinoflagellate cyst association. When the unicellular algae constitute 100% of a sample, the assigned temperature for that period is 24.1815 degrees Celsius; however, it is essential to note that the actual temperature may have been even higher. Precipitation is determined based on river discharge and is expressed as a proxy (Zonneveld et al., 2024). This data for Italy is invaluable, as local regions experience global climate shifts in their own way (Bavel et al., 2020). This dataset provides specific insights into Italy, aligning perfectly with the focus of this thesis. Furthermore, we used a second paleoclimatic dataset. Central European summer temperature and precipitation data were constructed using tree ring analysis for the years 400 B.C.E. – 2003 C.E. (Büntgen et al., 2011). This dataset contains reconstructed AMJ precipitation totals and JJA temperature anomalies. This data is available from the NOAA National Centers for Environmental Information (NCEI), under the World Data Service (WDS) for Paleoclimatology (NCEI, 2016).

2.2.2 Soil data
We sourced soil types, as well as soil pH data, from the European Soil Data Centre database (Panagos et al., 2022). Soil characteristics, such as soil organic nitrogen content and soil clay content were drawn from the Soilgrids database (ISRIC-World Soil, n.d.). LINTUL requires specific soil parameters, namely "sand" or "clay," to be selected when inputting soil information. We made these selections based on the soil properties identified within the Soilgrids datasets, where both sand and clay properties were found at all wheat locations, along with silt particles. Due to marginal differences in soil parameters across locations, we applied the same parameters to all locations. Although predominantly sandy, the presence of clay was notable enough to impact soil water retention. As a result, we decided to adjust the sand parameters by adding 1/5th of the difference between sand and clay to each parameter. The adjustment aimed to mimic sandy soil properties but with a bit more water retention, similar to sandy soil that contains some clay. For reference, Appendix 3 contains a table displaying the original sand and clay values alongside the adapted values tailored specifically for this thesis project. The soil parameters that we adapted in STICS were soil albedo, retrieved from a NASA dataset (2023), as well as soil pH retrieved from a European Commission dataset (2022), and clay content retrieved from Soilgrids (n.d.).

2.2.3 Climate data
To create an envelope of yield estimates, this study relied on the modern climate data of the CMIP6 project (Copernicus Climate Change Service, 2023). Climate models generate historical data by estimating past forcings, including Earth's orbital changes, greenhouse gas concentrations, volcanic eruptions, solar variations, and other historical records. These models simulate the historical period from around 1850 to 2014, using factors like CO2, CH4, N2O levels, solar changes, volcanic aerosols, human-induced aerosols, and land-use changes (McSweeney, 2018). The climate model that generates historical daily data for the country of Italy that we used is CMCC-CM2-HR4 (Scoccimarro et al., 2017), this is part of the CMIP6 project. We selected this dataset instead of recently measured weather data because it offers a historical record spanning more than 150 years. The temporal coverage of this dataset ranges from 1850 to 2014 on a daily scale. We selected the following variables: minimum temperature, maximum temperature, precipitation, and wind speed. Vapor pressure is not present in the CMIP6 dataset, and instead was calculated using the average temperature from the CMIP6 data (Vömel, 2011). We converted the climate data from NC-files to CABO files and csv's as part of the pre-processing stage. A CABO file is a file format that can contain historical weather data, this format makes weather data operational for crop growth models (Kraalingen et al., 1990). Using the study area coordinates, we extracted the minimum and maximum temperature values from the NC-files. We converted Kelvin values to Celsius and computed vapor pressure in kPa based on the average temperature NC-files. We calculated vapor pressure across the time range using the August-Roche-Magnus equation (Lawrence, 2005). We adjusted precipitation values, initially in $kg/m^2/s$, to millimeters per day (Bencini, n.d.). We extracted wind speed data, already in meters per second, from NC files and integrated all these parameters into the CABO files and csv's.

2.2.4 Daily solar radiation data
We developed daily solar radiation data based on mean monthly data for the years 2006 – 2022 from the Italian Solar Radiation Atlas (ISRA) (ENEA, 2022). We first aligned the study areas with selected solar irradiation locations from ISRA. For the ten chosen locations, we converted monthly values to kJ per m^2 and then interpolated them to obtain daily values spanning one year. These daily values were placed in the CABO files and csv's for each modern year from 1850 to 2014.

2.3 Crop management information
Landraces are unique genetic strains of wheat known for their ability to thrive in challenging conditions and maintain stable yields with minimal input. While they may produce lower yields compared to modern cultivars, they exhibit greater plant height and protein content. Local farmers actively preserve and share these landraces to prevent genetic erosion (Frankin et al., 2021). There is available knowledge about historic crops, for example, free-threshing wheat species like *T. aestivum* (Jaradat, 2013) that have been historically cultivated in Italy (Calvi et al., 2023). During Roman times, the predominant wheat variety cultivated in the northern regions of the country was bread wheat (*Triticum aestivum*), while in the southern regions, hard wheat (*Triticum durum*) was the primary choice.

As for the grape variety we have chosen to represent ancient grapes. Ancient Roman writers such as Cato, Varro, Columella, and Pliny (both the elder and younger) have documented the wine culture during Roman times. Among these authors, Pliny the Elder and Columella stand out for having written about various grape types and the qualities of the wine they produced. Pliny, for instance, has written about the Aminaeum grape variety, highlighting it as one of the finest options available during that era (Purcell, 1985). The existence of modern-day descendants of the Aminaeum grape variety is uncertain. However, it's worth noting that Pliny the Elder wrote about various other grape varieties as well. According to both Pliny and other Greco-Roman agricultural texts, the Raetica grape was popular as a white grape variety, and it was used to produce white wine in Raetia, a province of the Roman Empire. From an etymological and geographical perspective, the white 'Rèze' grape from Valais, Switzerland, appears to be the most promising candidate for a potential modern-day counterpart to the ancient Raetica grape. Four cultivars have been identified to have a parent-offspring relationship with the 'Reze' grape variety. These cultivars include: 'Cascarolo Bianco' (Piedmont, Italy), 'Arvine Grande' (Valais, Switzerland), 'Groppello di Revo' and 'Nosiola' (Trentino, Italy) (Vouillamoz et al., 2007). However, currently these variations are only grown in small specific regions in Italy, this provokes the question of whether these wine grapes were able to grow in other areas historically. It is therefore difficult to assume that these variations were historically grown in the study areas for this thesis research since these grapes are not cultivated in this region nowadays. Another study found that Sangiovese and Mantnico Bianco were cultivated south of the Campania region of Italy during Roman times (De Lorenzis et al., 2019). However, this does not imply that these grapes were grown in other parts of Italy and nowadays these grapes are grown in a smaller area north of Campania. To address the challenge of connecting modern grape varieties with their ancient counterparts, a study researching the genetic origins of ancient French grapevines was consulted. By examining archaeological grape seeds dating back to the Roman era, researchers identified genetic similarities between ancient and current grape variations. Specifically, they found strong genetic links between the Roman-era samples and modern varieties such as Savagnin Blanc, Pinot Noir, Amigne, Rousette, Arvine, Syrah, Humagne Blanche, and Alfrocheiro Preto (Ramos-Madrigal et al., 2019). However, it remains uncertain whether the ancient equivalents of these grapes were cultivated in Italy during the Roman period, given that the archaeological grape seeds were discovered within French territory (Ramos-Madrigal et al., 2019). Among the mentioned grape varieties, Syrah is nowadays grown in many provinces in Italy. Considering the historical connection to Roman times and their widespread cultivation throughout Italy nowadays, this grape variety appears to be the most suitable choice for use in this research.

2.3.1 Adapting LINTUL and STICS for ancient crops

Roman crops were different from modern-day crops. Ancient varieties produce lower yields than their modern descendants (Pourazari et al., 2015). In Roman Italy, there was a slow shift from hulled wheats to naked wheats, these naked wheats brought lower yields and the grain size was smaller (Heinrich, 2017). Furthermore, modern-day wheat has a smaller stem compared to ancient wheat varieties (Martínez-Moreno et al., 2020). Ancient literature does give some insights into the details of the yield of the crops in Roman times. The representation of the growth of ancient wheat crops required adjustments to the model's parameters. Evans (1981) provided insight into the characteristics of wheat growth during Roman times and details about crop yield, he also discussed how ancient agriculturalists viewed yield. Columella lived in the first century C.E. and owned farms in the area around Rome (Columella, 65 C.E./1941). According to Columella, a good and average yield for bread wheat on a normal field was around 1.2 tons per hectare. This amount computed is the estimated yield for a complete wheat field, diverging from Columella's described intercultivation method (Evans, 1981). To establish suitable *Triticum aestivum* parameters, we used Columella's yields as a calibration point for one location. Calibration was necessary to align our yields with those of ancient times. We chose wheat location three to calibrate the yields, this is the area in which Columella owned his agricultural fields (Columella, 65 C.E./1941). The process of calculating the yields for all locations involved using the calibrated parameters that were calculated in location three. However, applying Columella's yield threshold required matching modern climatic conditions to those of Columella's era in terms of temperature and precipitation, to find representative modern years. Columella resided in the RCO from 4 C.E. to 70 C.E. Marine core data provided insights into summer temperatures during this period (Zonneveld et al., 2024). The marine core data contains the summer temperature per three years for the years 200 B.C.E. to 600 C.E. (figure 3). By comparing average annual temperatures for August and September for the years 1850 to 2014 to the marine core data, we identified representative modern years for each ancient year. Notably, 1855 emerged as the most frequently representative year for the RCO, sharing similar temperatures with the marine core data and being the commonly chosen year when focusing on Columella's lifespan. Moreover, assessing 1855's precipitation revealed it to be a substantial yet not outlier level of precipitation, representative for the wet and warm RCO (Harper, 2019). We ensured that the spring temperature and precipitation levels were in line with the summer temperature and precipitation, avoiding extremes of heat or cold, excessive wetness or dryness, in comparison to the summer data for this year. This precaution is important as spring is the growing season for wheat. Specifically, April-May-June, aligning with the end of the vegetative stage for *Triticum Aestivum*, usually occurring in late April (OECD, 2006). The comparison of the average summer temperatures between the RCO and 1855 can be found in table 1. We based the calibration of the model on 1855, setting the yield as close as possible to 1.2 tons per hectare to represent Columella's era. We adapted the light use efficiency parameter in LINTUL from 3.00 to 1.20 to lower the yields to Roman times. The light use efficiency in modern crops is higher, due to selective breeding to improve yields (Sadras et al., 2012). Therefore we lowered this parameter to let the model represent ancient wheat growth. The calibration using Columella's yields focused on the first three locations for bread wheat (*Triticum aestivum).* Locations four and five were specifically designated for durum wheat cultivation. Romagosa et al. (1999) provided an estimated mean durum yield at the beginning of the first century, approximately 1.5 tons per hectare. This figure was used to calibrate the data for the year 1855, specifically for locations 4 and 5, resulting in yield estimates for durum wheat in these areas. The light use efficiency was set to 2.15 to represent durum wheat in Roman times.

Ancient grape cultivation differs from modern-day viticulture as well. Columella's writings describe the details of how the Romans cared for their vineyards and sought out the grapes with the best qualities and the largest yields. He describes the best quality vines as the ones that are strong enough to withstand periods of frost and do not rot when rain is abundant. Furthermore, the vine should flower early in the season, and ripen quickly (Columella, 65 C.E./1941). Columella describes average grape yields, which we used to calibrate the parameters of the STICS model. Bernigaud et al. (2021) modeled grape yields for the 1^{st} century B.C.E. for the south of France, and estimated yields to go up to 8.23 tons per hectare for irrigated grapes. Columella noted that approximately 2.74 tons per hectare was considered a low output, yielded by an underperforming vineyard. He gave the threshold of approximately 8.23 tons per hectare as the yield for a viable winery. Some vineyards produced higher yields, Columella gave an example of a young and exceptionally good vineyard that could produce 14.54 tons per hectare (Bernigaud et al., 2021; Columella, 65 C.E./1941; Robinson et al., 2006). These yields are comparable with Italy's current grape production, averaging at around 10.97 tons per hectare (Bernigaud et al., 2021; Robinson et al., 2006). We have chosen the yield estimate of 8.23 tons per hectare to calibrate the model. Using the same method of comparing the paleo marine core summer temperature and precipitation estimate to the modern weather data of Columella's farms near Rome, we found the year 1858 to be suitable for the calibration of the model. We checked if spring temperature and precipitation were in line with the summer data for 1858. Specifically, we selected April and May for grapes, taking into account the late budbreak, early flowering, and ripening characteristics of Syrah, as confirmed by the STICS model and literature (Robinson et al., 2006). We set the yield of that year as close as possible to 8.23 ton per hectare. To do this, we adapted the crop management parameters of Syrah in STICS. Details can be found in Appendix 4.

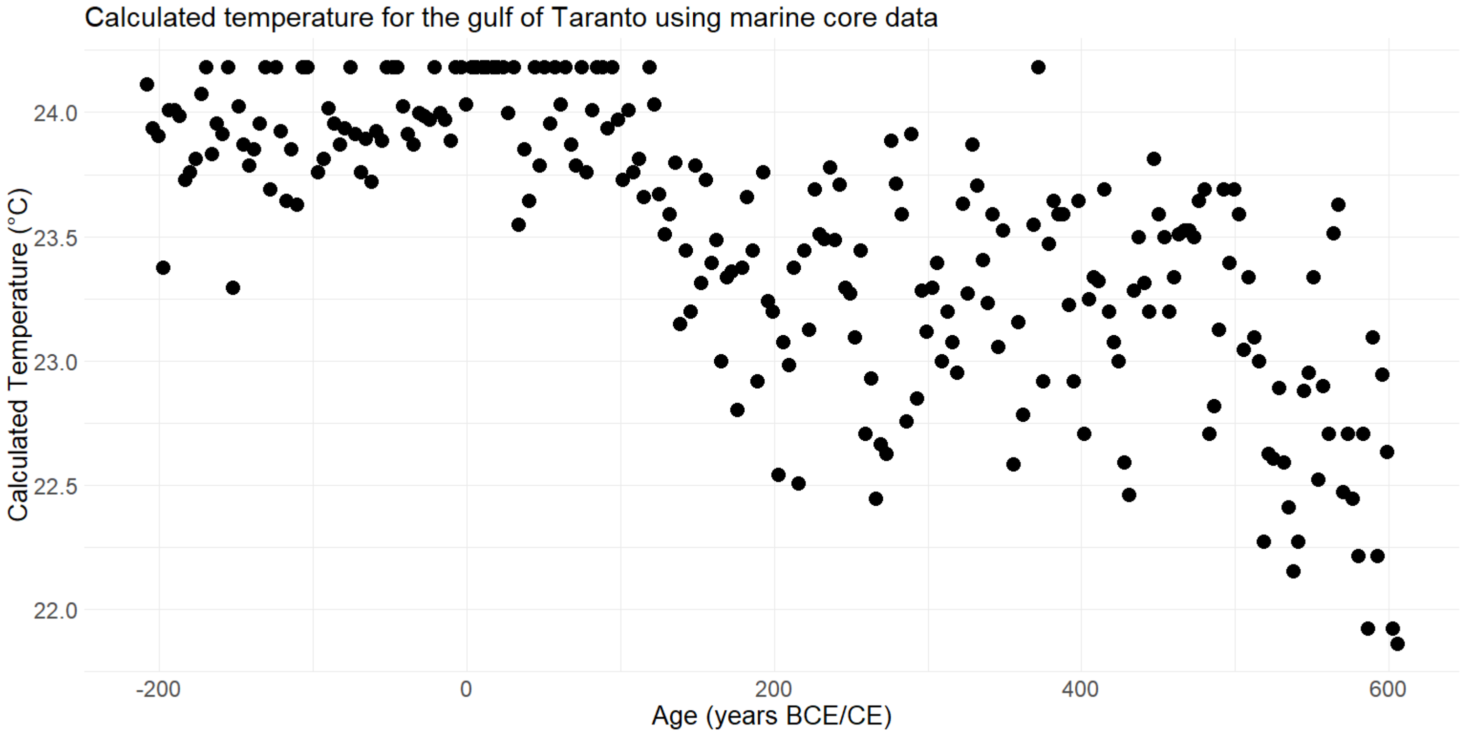

Figure 3: Calculated summer temperature using the marine core data from the gulf of Taranto (Zonneveld et al., 2024).

Table 1: Late summer temperature of the RCO (August & September) compared to 1855 for wheat location 3 and 1858 for the larger Rome area for grapes.

	RCO averages	1855	1858
Temperature in degrees C	23.9	24.1	23.5

2.4 Methodology

We used the LINTUL model to obtain wheat yields, and the STICS model to obtain grape yields, each for five locations spread over Italy, for the years 1850 – 2014.

2.4.1 Flowchart

Figure 4 represents the methodology to obtain yield envelopes that represent the RCO, the transitional period, and the LALIA.

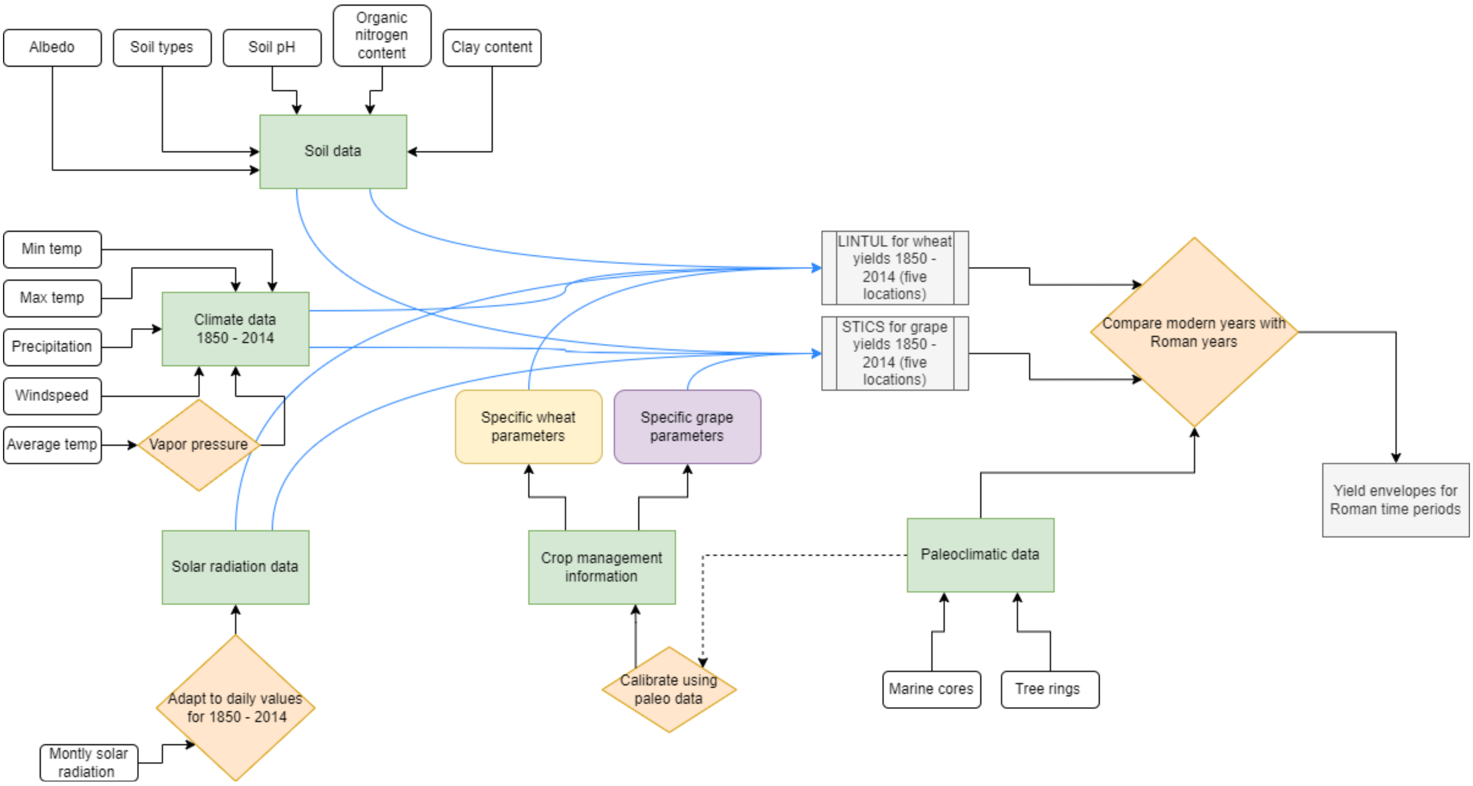

Figure 4: Flowchart of the methodology

2.4.2 Comparing modern climate data to Roman climate data

Italy's diverse landscape, characterized by many variations in elevation and vegetation, contributes to the country's climatic diversity. Italy is sensitive to temperature changes induced by greenhouse gas emissions (Coppola & Giorgi, 2010). Over the past century, the average temperature in Italy has risen by 1 degree Celsius (IEA, 2020). Addressing these changes, the CMIP6 CMCC-CM2-HR4 climate model accelerates the start of summer by introducing higher temperatures earlier in spring. However, this adjustment occasionally results in spring temperatures that are higher than the actual measured climate data for that year, creating a slight skew towards warmer conditions. To mitigate this, we compared the modeled data for spring to the most recent high spring average per location, and years exceeding this threshold were removed from the dataset. The temperature thresholds that were used can be found in Appendix 5. To get an understanding of the recent climate compared to Roman times, we compared the paleoclimatic data for the Gulf of Taranto with recent climate data for grape location four. This location is in the Gulf of Taranto area. The boxplots in figure 5 illustrate temperature data for late summer/early autumn in recent records and paleoclimatic data. The boxplot for paleoclimatic data appears slightly compressed due to the representation of percentages of unicellular algae in the samples. Specifically, temperatures exceeding 24.1815°C are not individually recorded but are instead grouped under the value 24.1815°C. Specific z-values in the modern data align with the exact paleoclimatic temperatures for the RCO, transitional period, and LALIA. Knowing these z-values allowed us to determine the corresponding yields for those temperature ranges. In contrast, there is no observable correlation between precipitation values in modern data locations, and the correlation with temperature is limited. The challenge arises from the paleoclimatic data, which uses a precipitation proxy (graded between 5 and 50). Consequently, it becomes difficult to establish a direct comparison between precipitation values in modern years and those in Roman times. We used z-values to compare modern climate data to the wet RCO and the drier later periods.

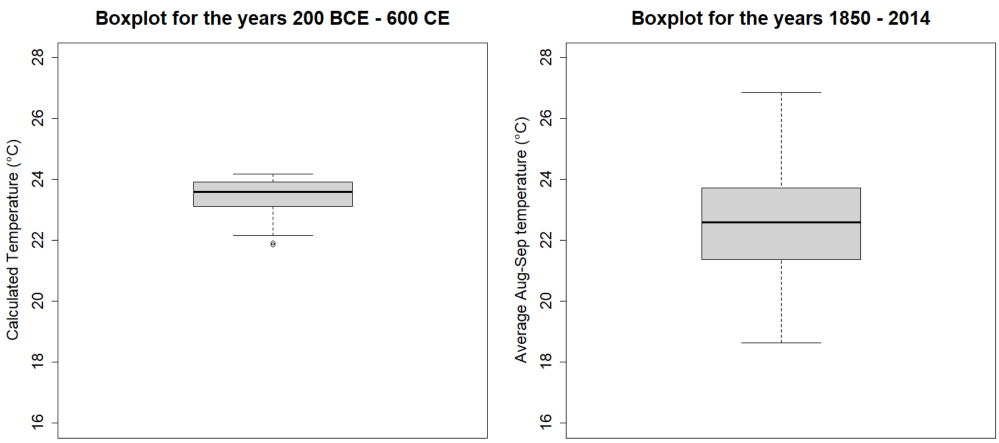

Figure 5: Boxplots of paleoclimatic marine core data for the gulf of Taranto and grapes location 4.

2.4.3 Testing LINTUL and STICS

To assess the impact of changing temperature and precipitation on the yields of wheat and grapes, and to gain insight into the behavior of the models, we ran model simulations using generated data. The data remained constant for each of the variables (solar radiance, wind speed, vapor pressure), but temperature or precipitation increased annually. Meaning that the daily temperature was consistent every day of the year, but this value rose with each year. Precipitation followed the same pattern. In one set of simulations, temperature varied while precipitation remained static, and vice versa in another set. All daily values for a given year shared the same variable conditions. The specific static variables used in running the models can be found in Appendix 6. We applied these models to simulate crop yields for both wheat and grapes at location three.

2.4.4 LINTUL wheat crop model

LINTUL-2 relies on soil type data, daily minimum and maximum temperature, precipitation data, daily solar radiation, daily vapor pressure, and daily wind speed (Hijmans, 2019). We ran LINTUL for each station and each year 1850 - 2014. We ran the model simulations for bread wheat across locations one to three and for durum wheat across locations four and five. The model results are for rain-fed yields.

2.4.5 STICS grape crop model

The STICS requires daily temperature data, daily precipitation, daily solar radiation, daily wind speed, daily vapor pressure, CO2 value, soil albedo when dry, soil pH, information about crop management, genetic parameters of the crop, and geographical information about the location of the crop (Brisson et al., 2003). We adapted these parameters to let Syrah be as representative of Roman grapes as possible. We ran the model for the years 1850 – 2014, the model calculated potential rain-fed yields without taking potential pests and diseases that might have influenced the crops into account. The results are in tons per hectare.

2.4.6 Creating yield envelopes

Running the models resulted in crop yields for all years. To construct yield envelopes representing yields during Roman times, we had to identify which yields corresponded to warmer RCO years and colder years. We used the marine core paleo data to find the temperature and precipitation ranges that correspond to the Roman late summer climate periods. Furthermore, to compare modern spring climate data to Roman spring climate data, we used a proxy. Indicating that spring temperatures in Lombardy during the RCO are comparable to those of the last decade of the 20th century (Büntgen et al., 2011; Leonelli et al., 2017).

3. Results

3.1.1 Test runs LINTUL and STICS

We ran test simulations for LINTUL and STICS using variable yearly temperature and precipitation data. We found that, in the case of wheat, there appeared to be an optimal temperature range for maximizing yield (Figure 6). However, due to the static nature of the variables and the absence of seasonal variations, we cannot conclusively state that the temperature range of 11 – 14 degrees is the most favorable for wheat. Rather, wheat exhibits a temperature optimum, and the exact temperatures may vary by location, influenced by other factors such as precipitation and solar irradiance. Wheat yields also responded positively to precipitation, with higher yields observed under increased precipitation (Figure 7).
In contrast, grape yields showed a gradual increase with rising temperatures until a threshold was reached, beyond which all yields failed (Figure 8). Regarding precipitation for grapes, an optimum was observed where yields increased slowly before decreasing again. Pinpointing this optimum to a specific range, like 1.2 to 1.7 mm per day, is challenging as it may shift in combination with other static parameters (Figure 9).

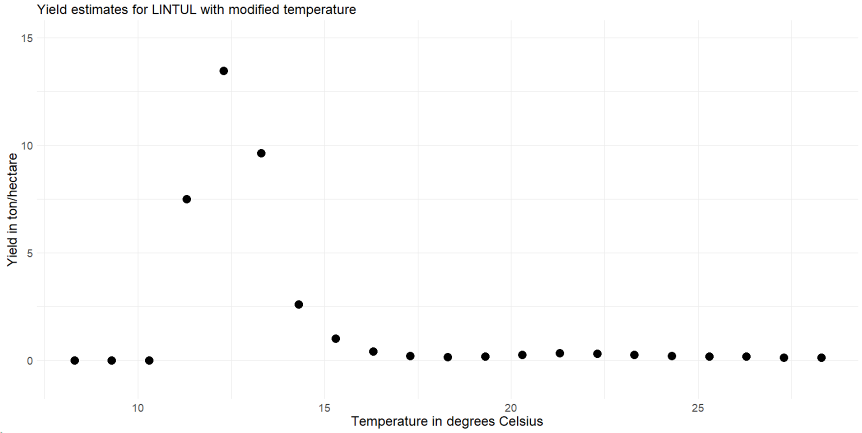

Figure 6: Yield estimates for bread wheat for LINTUL with static parameters and a variable temperature parameter. The temperature remains constant daily but increases every year.

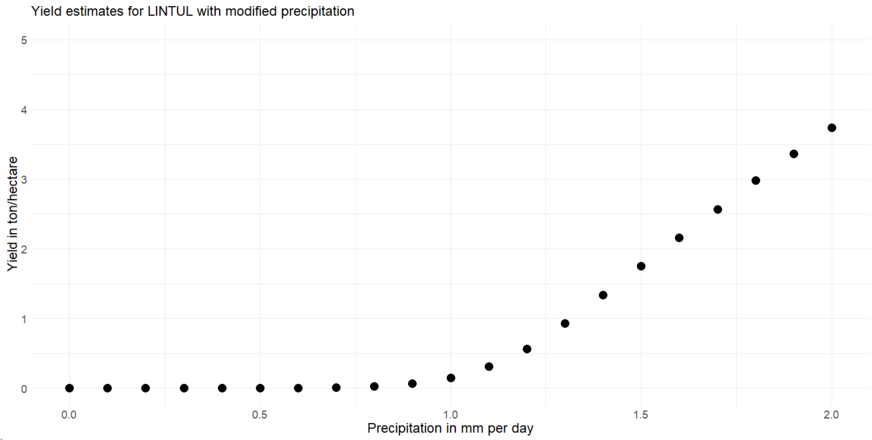

Figure 7: Yield estimates for bread wheat for LINTUL with static parameters and a variable precipitation parameter. The precipitation remains constant daily but increases every year.

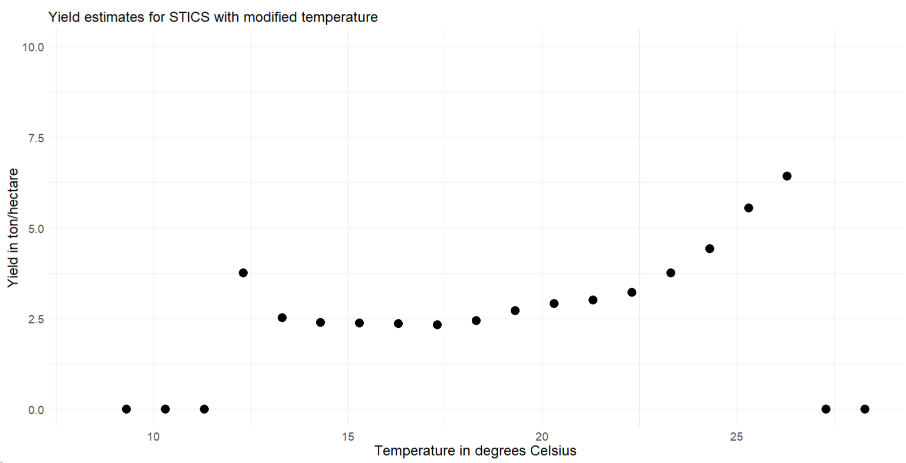

Figure 8: Yield estimates for Syrah grapes for STICS with static parameters and a variable temperature parameter. The temperature remains constant daily but increases every year.

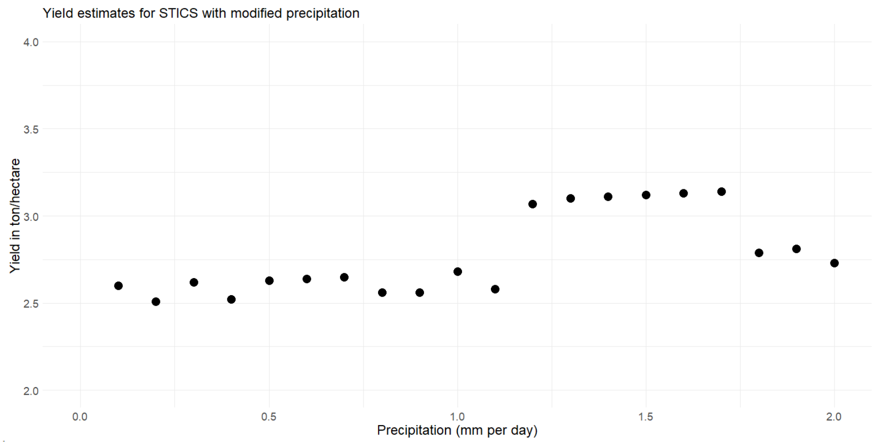

Figure 9: Yield estimates for Syrah grapes for STICS with static parameters and a variable precipitation parameter. The precipitation remains constant daily but increases every year.

3.1.2 Yield range

We have graphed the wheat yield against the spring (April, May, and June) precipitation (Figure 10) and spring temperatures (Figure 11). These graphs also show the z-values for spring precipitation and temperature. We find that especially spring precipitation is a significant factor influencing wheat yields (Figure 10). As precipitation increases, both the ranges and averages of yields show an upward trend. However, when examining locations three and two for wheat, a slight decline in averages and a lower upper threshold for the range is observed at the highest precipitation levels. This may indicate an excess of precipitation leading to decreased yields, although it could also be influenced by a lack of data points toward the end of the dataset that influence the averages. Furthermore, we observe a decrease in yields for both bread wheat and durum as we move farther south, which can be attributed to the lower rainfall levels in southern provinces. The impact of spring temperatures is less clear (Figure 11). Average yields tend to be high, even for the lowest temperatures in our records, reflecting the modern data's warmer tendency compared to Roman temperatures for spring. The lower values of the LALIA are not represented in these results. For example, the modern range of spring RCO temperatures for wheat at location one is approximately 17.70 degrees Celsius. However, for this location, the LALIA spring temperature at this location is estimated to be around 13.96 degrees Celsius, significantly lower than the lowest yield value depicted in the graphs based on modern data, which falls within the range of 15.60 to 16.20 degrees Celsius. Nevertheless, the findings suggest an optimum temperature for wheat growth, with excessively warm temperatures in spring, beyond those of the RCO, negatively impacting yields, highlighting the model's sensitivity to heat. While it would be expected, based on the test run for LINTUL, that there is a point at which wheat yields decline due to low temperatures, unfortunately, the model lacks sufficiently low spring temperatures to demonstrate this influence.

The spring (April and May) precipitation patterns for grapes present a less obvious trend (Figure 12). Notably, location one experiences unstable yields compared to the precipitation values and failed yields in almost all z-values. The failed harvests in all z-values might be contributed to the significantly colder climate compared to the other grape locations, causing grape development to occur later in the season (Oliveira, 1998). Locations two and three appear to hint that excessively low precipitation leads to lower averages. However, interpreting results for location three is challenging because there are only a few yield observations for the outlying precipitation values. Temperature appears to play a stronger role in grape yields (Figure 13). For locations two, four, and five we find higher yields for higher temperatures and lower yields for lower temperatures. Location three seems to show a slight decline, likely because it had fewer yields to offer due to excessive spring temperatures generated by the model, surpassing even the threshold of the highest recorded temperatures in the region We removed temperatures higher than the most recent highest spring, resulting in fewer yields available from this location. It's essential to note that for grapes, all temperature values skew toward the warmer side, making it challenging to assess grape yields at lower temperatures. Yields for colder LALIA temperatures are not represented by these spring temperatures, making it unclear how many grapes would have failed under such conditions.
Summer precipitation does not appear to impact grape yields (Figure 14). This absence of a clear pattern is expected, as, in most locations (excluding location one), grapes are fully grown at this time due to spring temperatures being high enough to develop early. Summer temperature only has a significant impact on grape yield for location one (Figure 15) with higher temperatures resulting in higher yields. This location, being cooler, develops grapes at a later time.

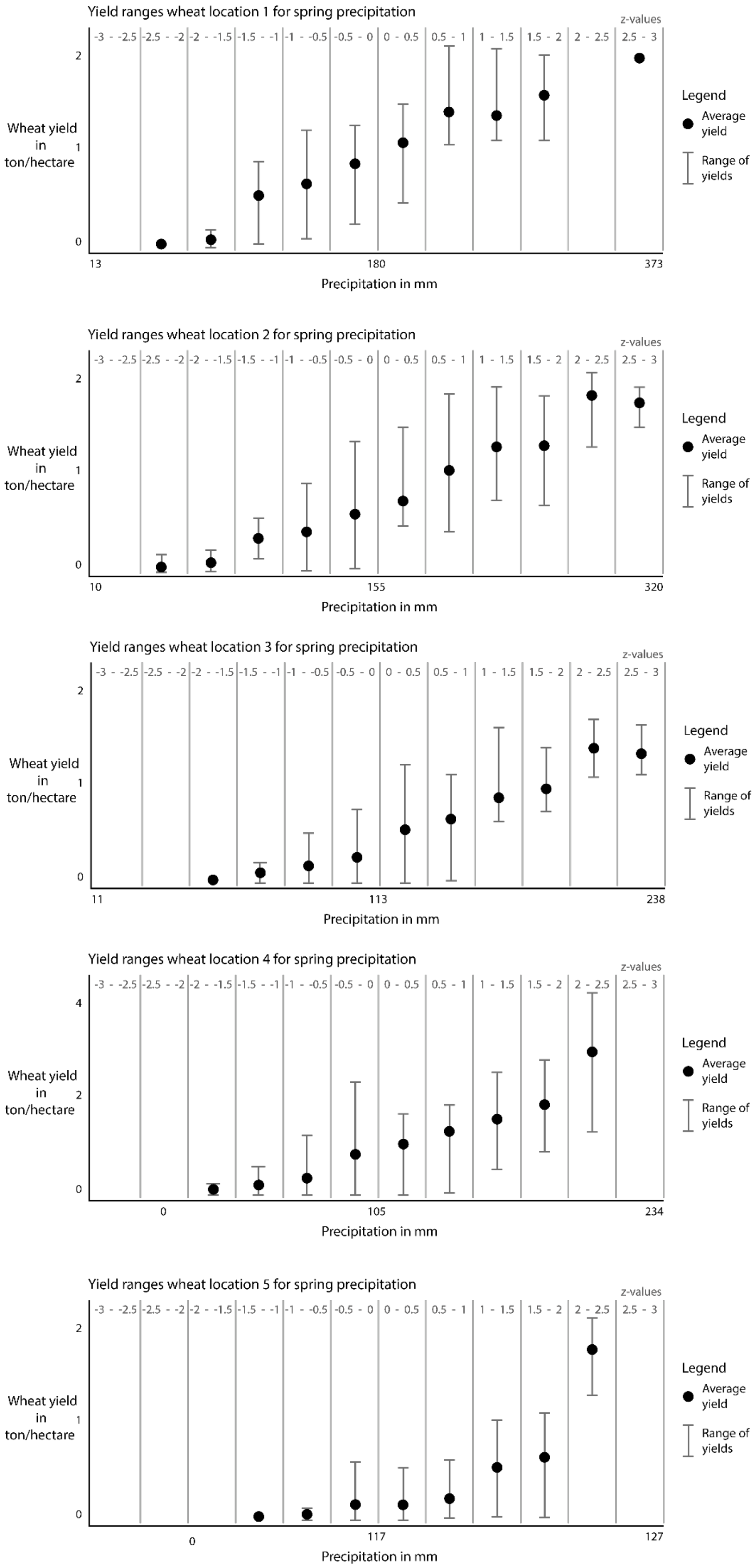

Figure 10: Wheat yield ranges and averages for spring precipitation. Locations one to three represent bread wheat, and locations four and five represent durum.

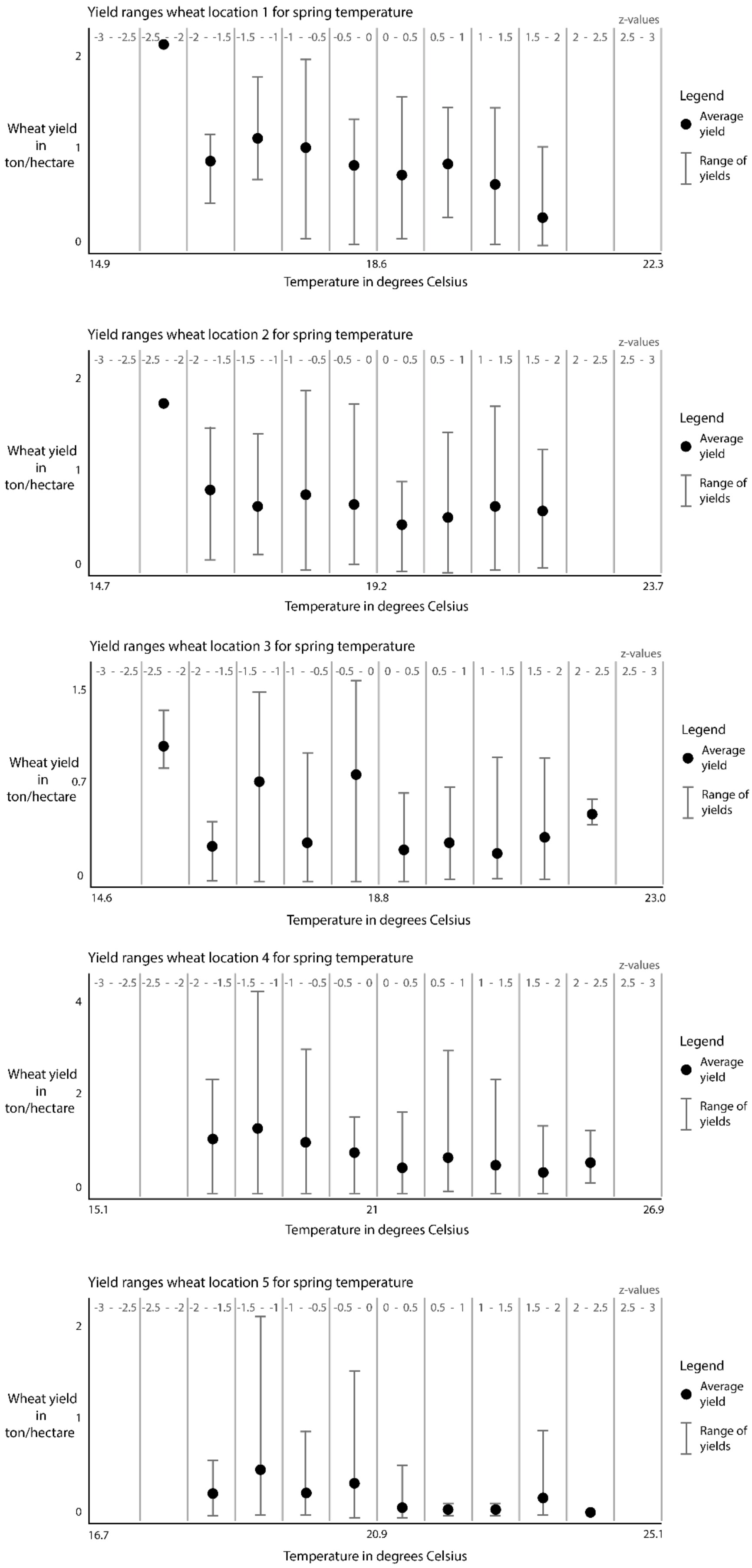

Figure 11: Wheat yield ranges and averages for spring temperature. Locations one to three represent bread wheat, and locations four and five represent durum.

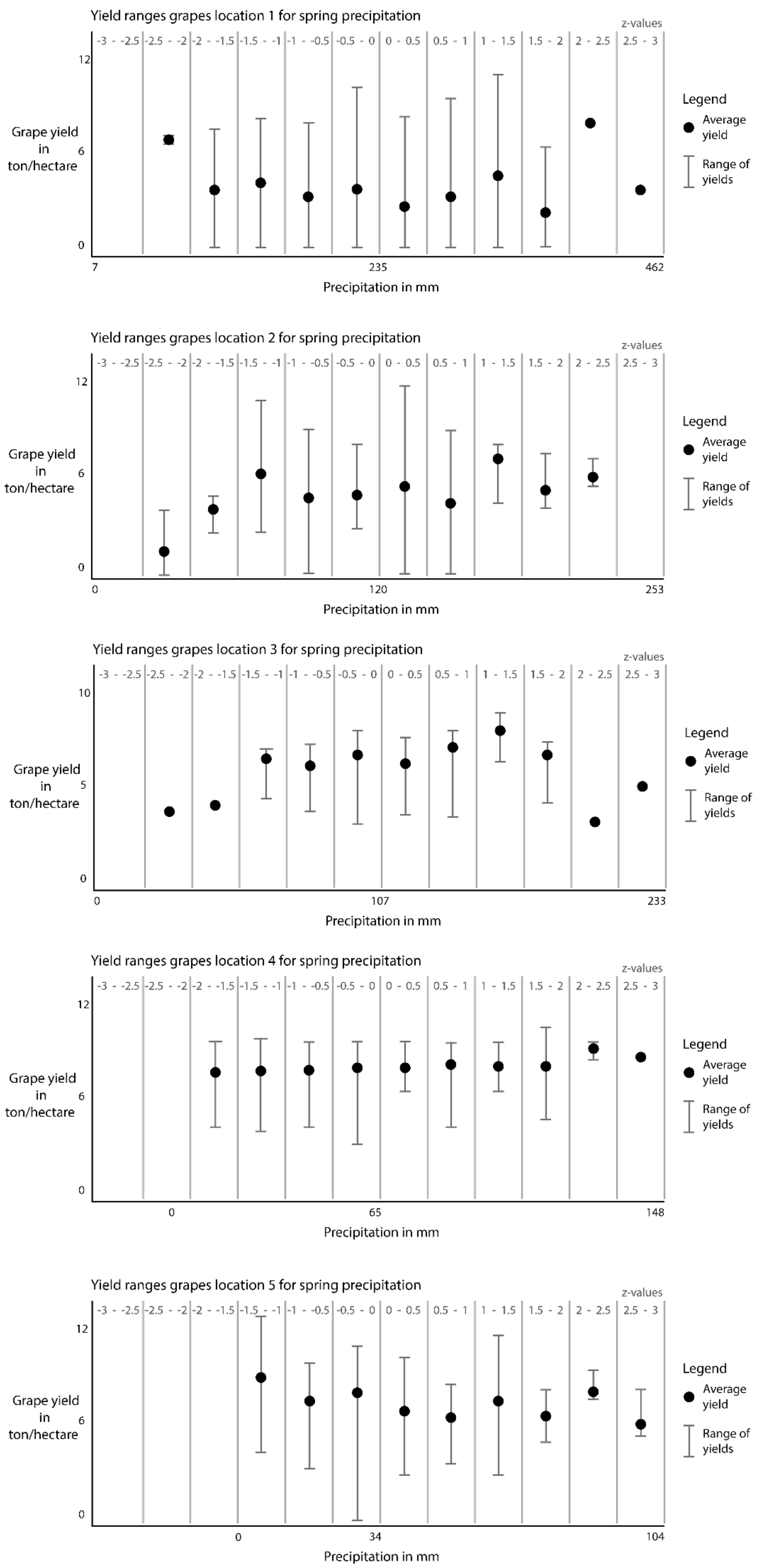

Figure 12: Syrah grape yield ranges and averages for spring precipitation.

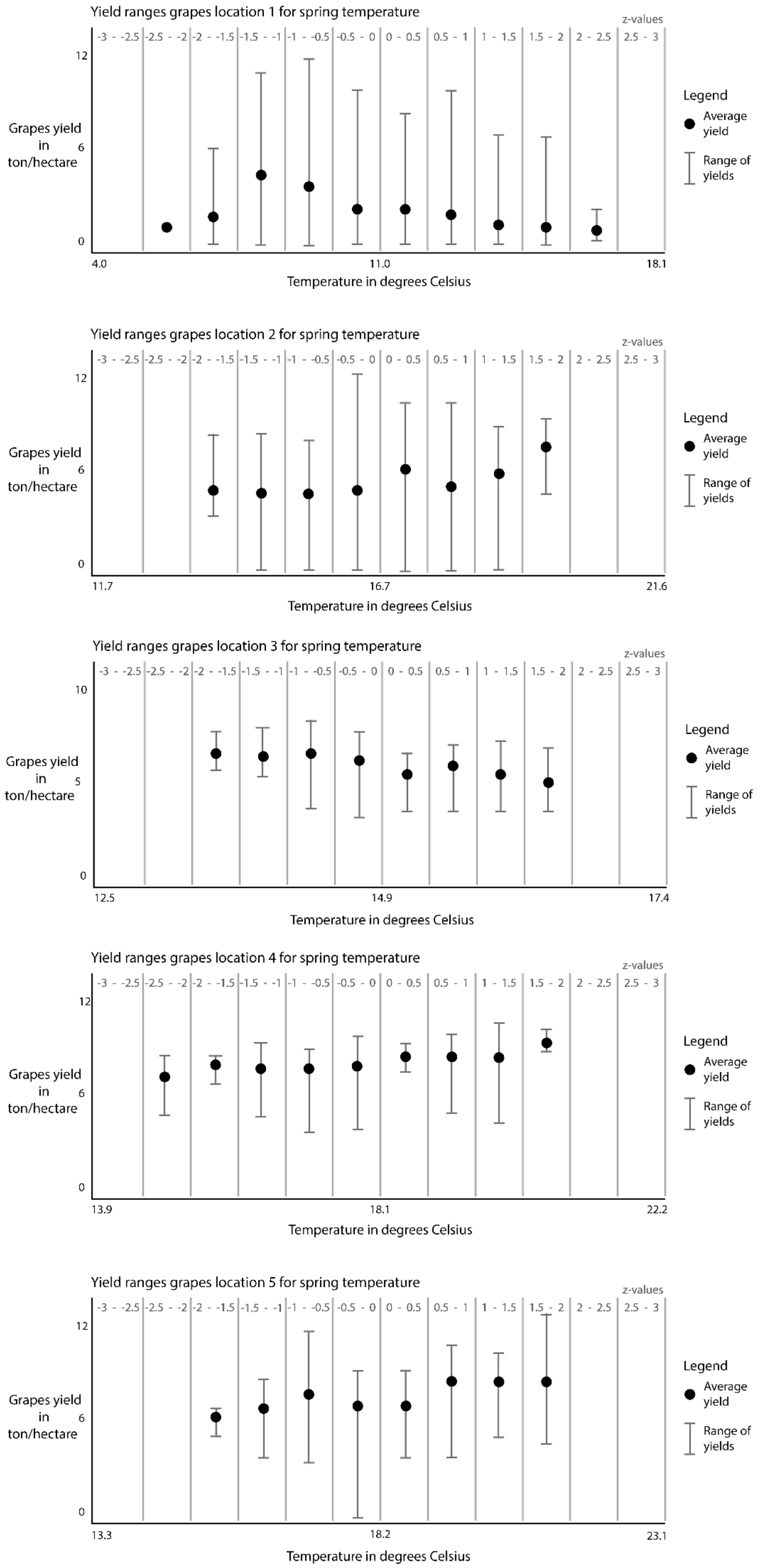

Figure 13: Syrah grape yield ranges and averages for spring temperature.

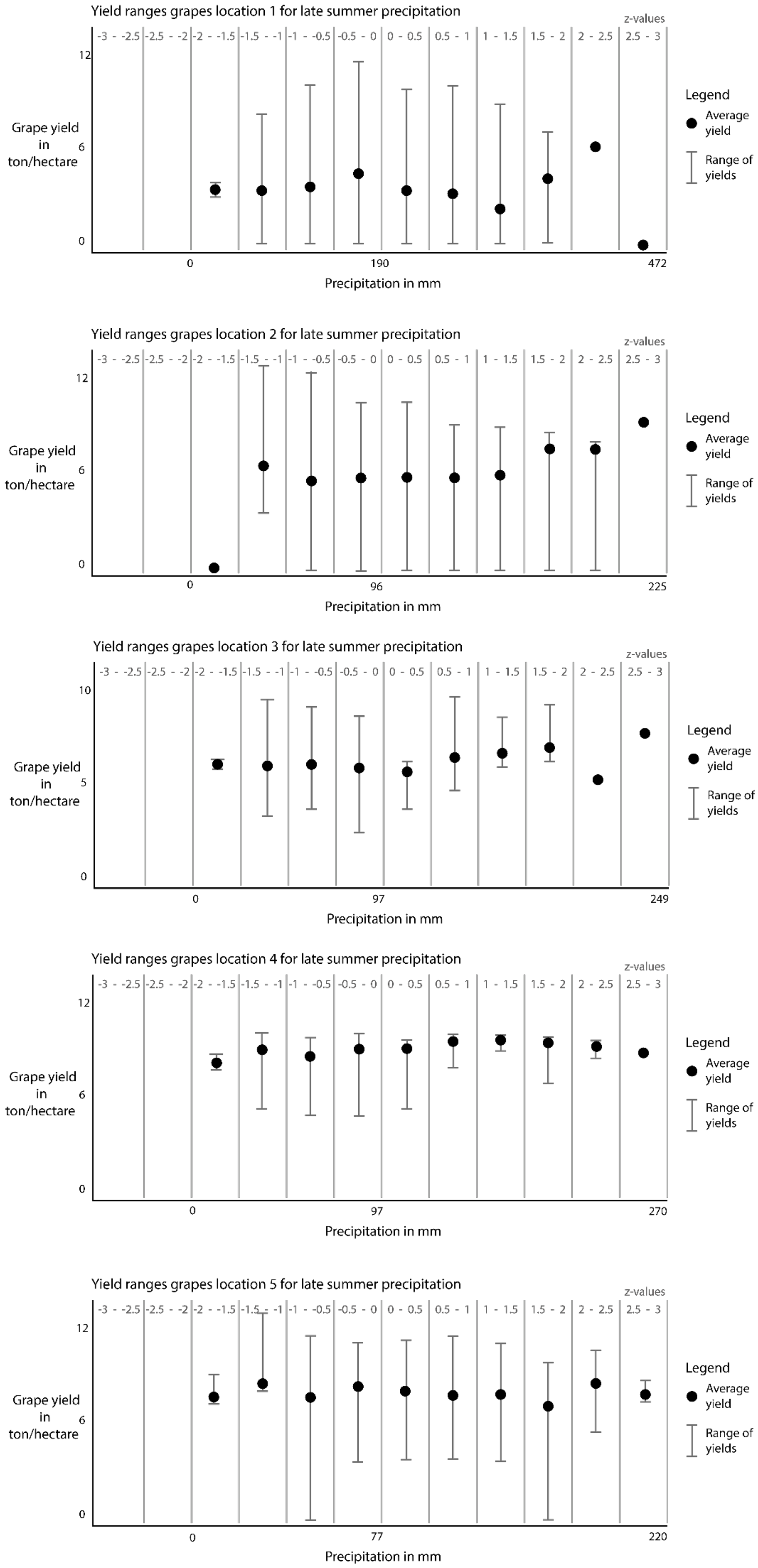

Figure 14: Syrah grape yield ranges and averages for late summer precipitation.

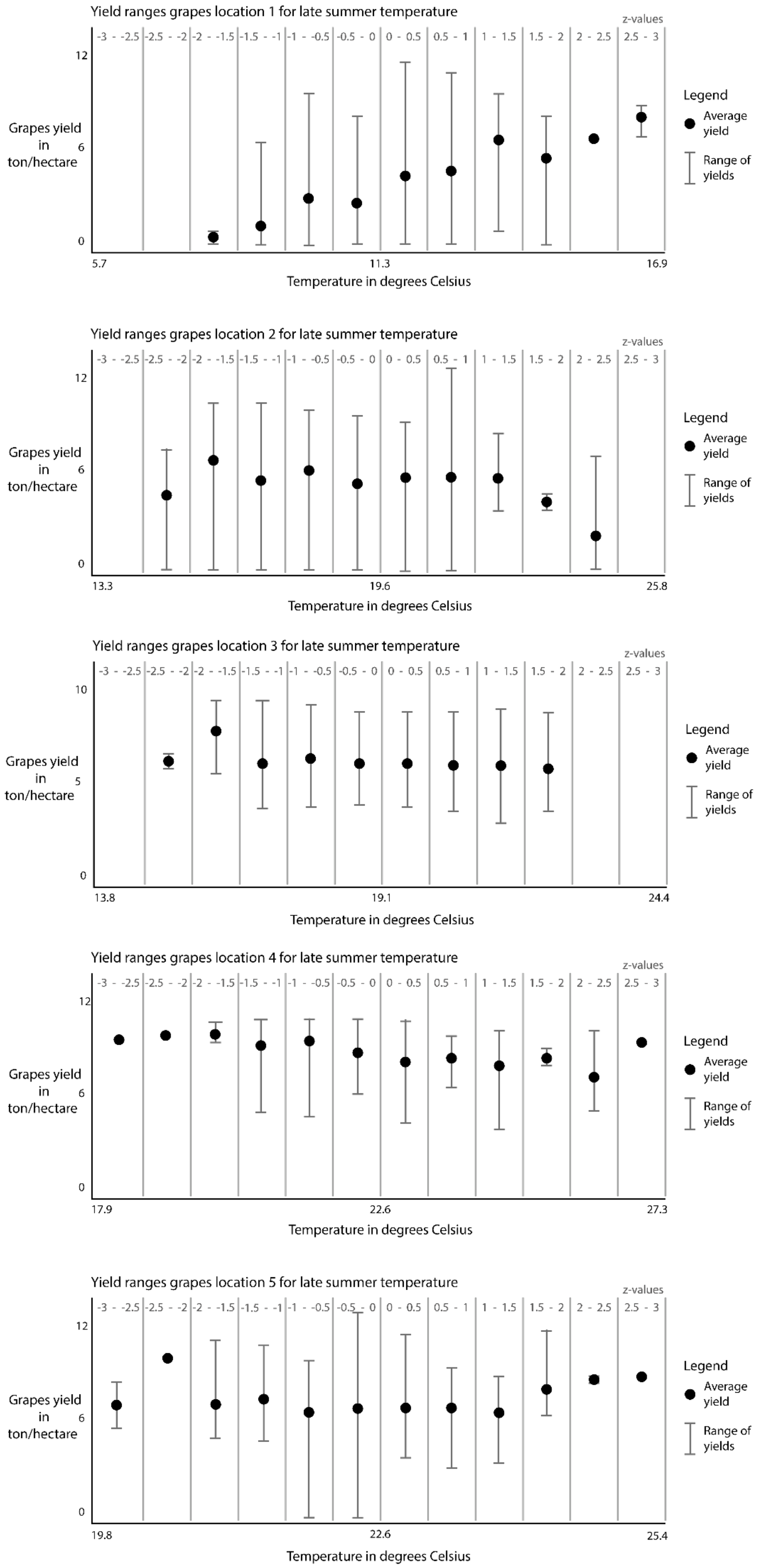

Figure 15: Syrah grape yield ranges and averages for late summer temperature.

3.1.3 Yield simulations in different Climatic periods

Table 2 displays the average wheat yields across three periods characterized by varying climatic conditions. The table represents yields linked to spring temperature and precipitation. The given z-value clusters represent the spring temperature and precipitation for the corresponding periods as well. We found that the average spring temperature (April, May, and June) in the last decade of the 20th century in the Lombardy region was approximately 17.5 - 17.9 °C. This is representative of RCO spring temperatures in this region. These temperatures correspond to z-values ranging from -1 to -0.5 for wheat 1, as it is situated in the Lombardy region. Since temperature is correlated across Italy, we examined the same z-values representing spring temperatures for wheat and grapes to evaluate yields under conditions similar to the RCO. The yields for the climatic period of the RCO (200 B.C.E. – 150 C.E.) are compared to a period inside the RCO where the mean spring temperature was lower, and the precipitation was higher compared to the RCO average (100 – 120 C.E.). The table compares yields to a second period at the end of the RCO where the temperature was lower but precipitation was at the same level as the RCO (130 – 145 C.E.). For several locations we were unable to find wheat yields because the climate data did not provide low enough temperatures to simulate the yields in the periods 100 - 120 C.E. and 130 – 145 C.E. In the available results, the period with higher precipitation (100 - 120 C.E.) displays yields surpassing those of the RCO. This aligns with expectations, looking at the graphs for wheat, where precipitation is a great influence. Despite the lower temperature during this period, the substantial impact of precipitation contributes to higher yields. There are almost no representative yields for the periods characterized by low temperatures and the same level of precipitation. The results show that the yield average for the one location that produced a result is substantially lower compared to the RCO average. We see a decrease of 51.8%. Based on this data, the pattern emerges where higher precipitation correlates with higher wheat yields, while lower precipitation corresponds to lower wheat yields.
We also compared the grape yields for the different climatic periods for spring (Table 3). Yields during the RCO and 100 - 120 C.E. periods appear very similar or show fluctuations in either direction. However, due to the constraints of the climate data, we have fewer yield simulations at the lower end of the temperature spectrum, with in some locations just one yield simulation. During the colder period (130 - 145 C.E.), some yields surpass those of warmer periods at the same location, some remaining equivalent, and others show lower yields. Drawing definitive conclusions from these spring temperature observations is challenging, given the possible role played by the scarcity of yields at the lower end of the temperature spectrum. More data at the lower spectrum would likely show more discernable patterns.

Lastly, we compared average grape yields across three periods representing summer temperature and precipitation (Table 4). These periods, namely 160 – 180 C.E. and 265 – 275 C.E., deviate from the periods used to compare spring yields. The reason was that summer temperature and precipitation were less warm-skewed, so colder periods could be chosen to compare yields. However not as cold as the LALIA. The first period (160 – 180 C.E.) has lower temperatures and the same precipitation level, while the latter (265 – 275 C.E.) exhibits both lower temperatures and lower precipitation. As expected, we find a decline in grape yield for location one for the lower summer temperatures, since grape yields in this region were not as much influenced by warmer spring temperatures. When comparing grape yields in the RCO average for this location to the colder and drier decade of 265 – 275 C.E., we see a major decrease of 78.1% in yields. Summer temperatures do not play a significant role for the other locations. The northernmost location shows that summer temperatures were crucial for grape yields in these parts.

Table 2: Comparing RCO average yields for wheat against a period with lower spring temperature and lower spring precipitation, and a period with both lower spring temperature and spring precipitation. The cells with no results signify that there were no yields found.

	RCO average yield	100 – 120 C.E. average yield	130 - 145 C.E. average yield
z-values	Temp = (-1 - -0.5) Precipitation = (-0.5 – 0)	Temp = (-2 - -1.5) Precipitation = (0 – 0.5)	Temp = (-2 - -1.5) Precipitation = (-0.5 – 0)
Wheat 1 spring	0.868 t/ha	-	0.418 t/ha
Wheat 2 spring	0.571 t/ha	-	-
Wheat 3 spring	0.051 t/ha	0.342 t/ha	-
Wheat 4 spring	0.105 t/ha	0.314 t/ha	-
Wheat 5 spring	0.158 t/ha	-	-

Table 3: Comparing RCO average yields for grapes against a period with lower spring temperature and lower spring precipitation, and a period with both lower spring temperature and spring precipitation. The cells with no results signify that there were no yields found.

	RCO average yield	100 – 120 C.E. average yield	130 - 145 C.E. average yield
z-values	Temp = (-1 - -0.5) Precipitation = (-0.5 – 0)	Temp = (-2 - -1.5) Precipitation = (0 – 0.5)	Temp = (-2 - -1.5) Precipitation = (-0.5 – 0)
Grapes 1 spring	1.12 t/ha	0 t/ha	5.98 t/ha
Grapes 2 spring	5.28 t/ha	5.31 t/ha	5.30 t/ha
Grapes 3 spring	6.61 t/ha	6.32 t/ha	-
Grapes 4 spring	7.10 t/ha	8.27 t/ha	-
Grapes 5 spring	8.16 t/ha	-	6.91 t/ha

Table 4: Comparing RCO average yields for grapes against a period with lower summer temperature and similar summer precipitation, and a period with both lower summer temperature and summer precipitation.

	RCO average yield	160 – 180 C.E. average yield	265 – 275 C.E. average yield
z-values	Temp = (0.5 – 1) Precipitation = (-0.5 – 0)	Temp = (-0.5 – 0) Precipitation = (-0.5 – 0)	Temp = (-1.5 – 1) Precipitation = (-1 – 0.5)
Grapes 1 August-September	6.00 t/ha	2.22 t/ha	1.31 t/ha
Grapes 2 August-September	2.99 t/ha	3.41 t/ha	4.91 t/ha
Grapes 3 August-September	6.56 t/ha	6.63 t/ha	4.90 t/ha
Grapes 4 August-September	8.69 t/ha	8.60 t/ha	8.20 t/ha
Grapes 5 August-September	7.73 t/ha	7.60 t/ha	7.95 t/ha

4. Discussion

In the period after the Roman Climate Optimum (RCO), starting in the second half of the second century, and beyond, there was a shift away from stable climate conditions, resulting in a period of cooling around the Mediterranean. The Late Antique Little Ice Age which started around 536 C.E. resulted in dramatic temperature decreases (Peregrine, 2020) and strong declines in precipitation (Büntgen et al., 2011). Our simulation models demonstrated that wheat yields are strongly dependent on spring precipitation. Northern locations yield more due to higher precipitation in these areas. This corresponds with others who have found that wheat yield variability is mainly caused by precipitation and landscape orientation of the crop (Basso et al., 2009, 2012; Dalla Marta et al., 2015; Erdkamp, 2012; Yu et al., 2014). Others however have indicated that too much precipitation can be equally detrimental, especially if temperatures remain low (Dermody et al., 2014). Our results did not support a strong influence of spring temperature on wheat yields. Increasing maximum temperatures, even higher than the RCO ranges, can have a negative impact on wheat yields, while increasing precipitation generally has a positive impact (Yu et al., 2014). One possibility is that wheat demonstrates a greater sensitivity to temperature when colder LALIA years are modeled in addition to these results, as indicated by the test run conducted with LINTUL, which identified an optimal temperature threshold for wheat. By further modeling the LALIA years for wheat, it's possible to pinpoint the specific range on the temperature scale that constitutes the optimum conditions for wheat growth in each location.

We have found that summer temperature only impacts grape yields in the most northern location, but that there is no significant impact of summer precipitation. Potopová et al. (2015) confirm that summer precipitation does not influence grape yields very much. High spring temperatures produced by the climate model advanced the ripening period of grapes (Leeuwen & Darriet, 2016). If spring temperatures were lower we would expect a later development of the grapes, resulting in a more distinct influence of summer temperatures on grape yields. A notable exception is the distinct influence of temperature on grapes in the most northern location. This colder location represents a temperature-yield trend that would be expected in other locations.

The wider implications of our findings suggest a significant connection between high precipitation and increased yields for bread wheat and durum adapted to Roman standards. This observation is intriguing in the context of the post-RCO period, where precipitation became more variable during the transitional period and the LALIA. While there was insufficient representative data to model the LALIA explicitly, it is clear that wheat yields were influenced by precipitation. The Romans would likely have experienced lower wheat yields in years with reduced rainfall. A parallel link may exist for temperature and grapes, particularly evident in the case of colder location one, which was less affected by excessively warm spring temperatures. Here, a clear association between temperature and grape yields is visible, indicating that higher yields were possible due to higher temperatures in late summer. The value of this analysis lies in its ability to display the complexity of ancient agricultural systems within Italy. Variations in effects across regions, seasons, and climate variables indicate the importance of understanding the nuances of each location.

To put these findings within the framework of the Roman Empire, it's crucial to understand the significant roles played by wheat and grapes in antiquity. Cereals were the predominant food eaten from 1000 B.C.E. to 500 C.E., and large estates dedicated to farming and trading grain served as the primary source of wealth for the Roman elite during the late Republican and early Imperial periods (Erdkamp, 2012). Wine was the most commonly drank alcohol in the Mediterranean in Roman times, and the only widely available intoxicant. This made wine high in demand, making grape cultivation a vital economic activity (Purcell, 1985). The success of these crops was inherently tied to weather conditions. In many regions of the Mediterranean, the average rainfall per year is just sufficient for cultivating grain. Southern Italy, in particular, was susceptible to failed harvests due to droughts (Erdkamp, 2012). Between 500 B.C.E. and 500 C.E., the Romans recorded at least 35 major famines, highlighting the vulnerability of agricultural systems (Manning, 2004). In cases of not enough spring precipitation or an early onset of summer, yields would drop (Erdkamp, 2012), this early onset of summer potentially explains the yield peak at lower spring temperatures for wheat in the results. Extreme hot spring temperatures generated by the model resulted in lower yields, indicative of an earlier summer. Ancient Romans managed these weather fluctuations through crop diversification on their plots of land, planting various grains and legumes. This approach allowed them to mitigate the impact of unfavorable weather conditions on specific crops (Erdkamp, 2012). Climate change has been identified as a potentially significant force influencing ancient societies (Marx et al., 2018). In the context of the fall of the WRE, climate change has been considered one of several potential influential causes, alongside lower birth rates, class conflicts, economic instability, high tax burdens, civil wars, military instability, corruption, bureaucracy (Marx et al., 2018), and pandemics (Harper, 2019).

In a reflection on the method used. There is still a research challenge at hand, namely to determine whether Syrah can be considered an accurate modern equivalent of ancient grape varieties grown in Italy. This challenge arises due to the uncertainty surrounding whether this grape variety was cultivated in Italy during ancient times, as much of the historical information documented by the Romans regarding the modern-day descendants has been lost.

The paleoclimatic data derived from marine cores has given the value 24.1815 degrees Celsius to the 100% saturation point for the samples, suggesting that temperatures during the RCO might have been even higher than recorded. Determining the actual extent of how high these would be and its correlation with crop yields poses a challenge. There is an expectation that temperatures might reach a point where they are too high to optimize yields, but it is difficult to conclude if this was the case for the RCO since the top temperature values are not clear.

Solar radiation was given the same values for each modeled year, a method deemed preferable to using global values, although the exact potential influence of solar radiation on crops remains unclear. Yu et al. (2014) state that, under normal precipitation levels, wheat crop yields are strongly influenced by solar radiation.

As LINTUL is a simplistic crop model, the primary distinction in modeling durum and bread wheat lies in the adapted Light Use Efficiency. While in reality many differences can be found comparing durum and bread wheat in their behavior, integrating such complexity into the model proved challenging.

The model calibration relied on data from 1855 and 1858, representing RCO summer temperatures. Due to the model's skew towards warm spring temperatures, determining if these years were the optimal representation for spring remains challenging. Despite efforts to ensure the years were not excessively warm in spring and had sufficient precipitation to represent the RCO, this remains an educated guess. The yields from these calibration years are higher than other yields, aligning with expectations.

Spring temperatures are used to find the climate's influence on yields, but the potential impact of early spring and mid-summer on yields might be overlooked in the graphs. This could explain instances where similar precipitation and temperature result in different yields. While wheat is harvested in July, minimizing the impact of summer, grapes continue to grow through the season. This shows the limitation of the graphs with averages for temperature and precipitation, as they do not consider the influence of other months.

5. Conclusion

Modern climate data from 1850 to 2014 can to a certain extent be used to model crop yields of landrace spring wheat and wine grapes. However, the modern data falls short in accurately capturing the colder conditions of the LALIA, due to its overall warmer temperatures, particularly during the crucial spring growing season for wheat and grapes. This bias results in an incomplete representation of the temperature range experienced by the Romans after the Roman Climate Optimum. Paleoclimatic data confirms that spring temperatures for the colder and drier periods are not well represented by modern climate data. The cooler and more variable climate in the transitional period and LALIA are not represented in full, given the absence of yields for such climatic situations. Nevertheless, the modern data proves effective in modeling wheat and grape yields during the RCO.

We determined the yield ranges for both bread wheat and durum across multiple locations in Italy using the LINTUL crop growth model. Under specific conditions, yields varied, with success observed in some instances and failure in others. The primary influence over yields proved to be precipitation levels, displaying a positive correlation between high precipitation and high wheat yields, while yields failed under conditions of low precipitation. Temperature displayed a lesser influence on wheat yields, with lower spring temperatures associated with a small rise in yields. This phenomenon can be attributed to the spring data being skewed towards the warmer side of the spectrum, and these lower spring temperatures aligning with what would have been considered high temperatures in Roman times. Consequently, it remains uncertain how lower temperature variations beyond the dataset's scope would impact yields, comparable to those in the transitional period and the LALIA. Anticipating lower precipitation and temperature in the later years of the Roman Empire, coupled with the established correlation between precipitation and yields, we expect wheat yields to be lower during these later periods.

As for grape yields, we ran the STICS crop growth model across five locations in Italy to obtain Syrah grape yields. In our exploration of the results, temperature emerged as the strongest determining factor. Nevertheless, modeling the full range from the LALIA to the RCO proved challenging for grapes. This limitation stemmed from excessively high spring temperatures, influencing the advanced ripening of the grapes and failing to capture the colder spring temperatures characteristic of the transitional period and the LALIA. Among the grape locations, location one showed a lesser bias towards warmer spring temperatures, given its location in a colder region where summer was not advanced too much by the climate model. Notably, in this location, a strong correlation emerged between low summer temperatures and failed yields, and high summer temperatures and high yields. We expect that similar temperature-yield trends would occur in other locations when modeling colder years representative of the transitional period and the LALIA.

Wheat and grapes were the most important foods for the Romans, with both the wealthy and the poor heavily relying on these crops. The vulnerability of these crops to climate change posed challenges for the Romans, who were not always fortunate enough to experience the optimal climate conditions of the RCO. In years where spring precipitation was low or summer came too early, wheat crops faced the risk of failure. Similarly, grapes were susceptible to climate change and temperature fluctuations. These historical facts in combination with the model results highlight the significance of an optimal climate in yielding high production for wheat and grapes during the RCO. However, data representing the transitional period and the LALIA are not represented in these models to estimate wheat and grape yields for these periods. Further research is needed to bridge this knowledge gap for the colder periods. In the near future, the models can be rerun using adapted colder climatic data. The hypothesis is that grape and wheat yields would be lower during these periods, providing evidence that climate change had a negative impact on the agricultural society of the Romans and potentially contributed to the downfall of the Empire.

6. Recommendation

Future research could explore modeling crop yields for different regions within the Roman Empire, extending beyond Italy. Places like Egypt or Gaul present interesting possibilities for analysis during this climatic period. Given the current climate model's bias towards warmer temperatures in spring, an interesting direction for future research would be to explore alternative climate models that better represent colder years. Another option to obtain yields for the colder periods would be to run the models for regions with colder climates such as Germany or Poland. These regions could provide colder spring temperatures similar to those experienced during the LALIA. Alternatively, a possibility would be adjusting the existing model to incorporate colder temperatures, by adapting the data of the current climate model, whilst factoring in all relevant weather variables. Another possibility is the use of climate data modeled specifically for the historical period, for example, a dataset provided by Shi et al. (Shi et al., 2022) though such datasets might lack specificity for Italy itself.

A valuable extension of research efforts could involve considering the entire growing and maturing season when modeling crop yields. This could mean calculating whether a year is consistently warm or consistently cold or if there are extreme temperature variations during weeks not represented in the graphs. Excluding years with unusual hot or cold periods from grape modeling could ensure that all yields are derived from fully representative years.

7. References

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Appendix

Appendix 1: Full description of chosen study areas

Geographical description of each area

To clarify the differences between each area, each of them has been given a name regarding their geographical location. These areas will be briefly described in their geographical context.

1. Wheat Po valley

The study area is situated in the Po Valley, a low-lying and fertile region known for its robust agricultural practices.
Wheat variety grown: *Triticum aestivum*
Elevation: 13 meters above sea level
Soil group: Cambisols

2. Wheat Apennines

This study area is located in the Apennines mountainous region.
Wheat variety grown: *Triticum aestivum*
Elevation: 300 - 750 meters above sea level
Soil group: Cambisols

3. Wheat Lazio

The study area is situated along the Tyrrhenian Sea coast.
Wheat variety grown: *Triticum aestivum*
Elevation: 50 - 185 meters above sea level
Soil group: Luvisols

4. Wheat Puglia

This study area is located in southern Italy, in the geographical region of Puglia, characterized by its fertile plains.
Wheat variety grown: *Triticum durum*
Elevation: 320 - 420 meters above sea level
Soil group: Luvisols

5. Wheat Sicilia

This study area is located in central Sicily, lying at a higher altitude characterized by lakes and rivers.
Wheat variety grown: *Triticum durum*
Elevation: 350 meters above sea level
Soil group: Vertisols

1. Grapes Po valley

The study area is located amidst a small region of rolling hills in the fertile Po Valley, with an elevation higher than that of the surrounding Po Valley.
Elevation: 100 – 400 meters above sea level
Soil group: Cambisols

2. Grapes Florence

This study area is located in the mountainous area of the Apennines.
Elevation: 250 – 600 meters above sea level
Soil group: Cambisols

3. Grapes Abruzzo

The study area is situated approximately 15 kilometers from the East Coast and features a hilly terrain.
Elevation: 150 – 350 meters above sea level
Soil group: Cambisols

4. Grapes Puglia

The study area is positioned at the southeastern tip of Italy, and it is characterized by its low-lying terrain, situated in proximity to the coast.
Elevation: 55 – 80 meters above sea level
Soil group: Luvisols

5. Grapes Sicilia

The study area is situated on the western side of Sicily.
Elevation: 50 – 200 meters above sea level
Soil group: Luvisols

Appendix 2: dataset description

Dataset	Data description	Units	File type	Used in model	Source
CMIP6 climate projection CMCC-ESM2	Daily maximum near-surface air temperature from 1850 to 2014	K	NC file	LINTUL & STICS	(Copernicus Climate Change Service, 2023)
CMIP6 climate projection CMCC-ESM2	Daily minimum near-surface air temperature from 1850 to 2014	K	NC file	LINTUL & STICS	(Copernicus Climate Change Service, 2023)
CMIP6 climate projection CMCC-ESM2	Near-surface air temperature from 1850 to 2014	K	NC file	Result Interpretation	(Copernicus Climate Change Service, 2023)
CMIP6 climate projection CMCC-ESM2	Near-surface wind speed from 1850 to 2014	m s-1	NC file	LINTUL & STICS	(Copernicus Climate Change Service, 2023)
CMIP6 climate projection CMCC-ESM2	Precipitation from 1850 to 2014	kg m-2 s-1	NC file	LINTUL & STICS	(Copernicus Climate Change Service, 2023)
Tabel values of Solar Radiation in Italy	Direct Normal Irradiance, daily monthly averaged for 243 locations for 2006 - 2022	kWh/m²	Excel file	LINTUL & STICS	(Wu et al., 2018)
Soilgrids	Soil clay, sand, and silt content	g/kg	Tif file	LINTUL & STICS	(ISRIC-World Soil, n.d.)
Soil ALBEDO	Soil albedo data	Reflection	-	STICS	(NASA, 2023)
LUCAS 2018 soil module	Soil pH	pH	Shapefile	STICS	(European Commission. Joint Research Centre., 2022)
Russian Altai and European Alps 2,000 Year Summer Temperature Reconstructions	Paleoclimatic temperature and precipitation reconstruction using tree rings	Mm & C	Excel file	-	(NCEI, 2016)
Climate change, society, and pandemic disease in Roman Italy between 200 BCE and 600 CE	Paleoclimatic temperature and precipitation reconstruction for the Gulf of Taranto	Precipitation proxy & C	Excel file	-	(Zonneveld et al., 2024)

Appendix 3: adapted soil parameters

Parameter	Units	sand	clay	Adapted for Italy
Maximum rooting depth	M	0.6	1.2	0.72
soil water content at air dryness	m3 m-3	0.05	0.08	0.056
soil water content at wilting point	m3 m-3	0.08	0.20	0.104
soil water content at field capacity	m3 m-3	0.16	0.46	0.22
critical soil water content for transpiration reduction due to waterlogging	m3 m-3	0.40	0.49	0.418
soil water content at full saturation	m3 m-3	0.42	0.52	0.46
max drainage rate	mm d-1	50	50	50

Appendix 4: STICS parameters

Adapted parameters plant and genotype: “vine_Syrah_plt.xml”

Parameter	Original value	Adapted value
Afruitpot	1.12	5

We adapted the plant parameters in the vine_SYRAH_plt.xml file. Specifically, we modified the 'afruitpot' parameter, increasing it from 1.12 to 5. This parameter signifies the maximum number of set fruits per inflorescence and degree day (for indeterminate growth) and we have raised it compared to the initial setting. The purpose behind this adjustment is to set the yields to match the levels observed in Columella's farms.

Adapted parameters soils: "solvigne.xml"

	Original value clay content	Adapted value clay content	Original value albedo	Adapted value albedo	Original value pH	Adapted value pH
Soil location grapes 1	25	34	0.22	0.13	7	7.97
Soil location grapes 2	25	26	0.22	0.13	7	7.51
Soil location grapes 3	25	36	0.22	0.16	7	8.10
Soil location grapes 4	25	30	0.22	0.17	7	7.96
Soil location grapes 5	25	37	0.22	0.17	7	8.15

We established soil albedo by referencing the mean values of July and January 2023 for each location, as reported by NASA. This approach allowed us to simulate the complete yearly range of albedo. For soil pH in water solution, we adapted the values to each specific location. Additionally, we calculated the clay content as a percentage using data from Soilgrids. To create five distinct soil files, we used information from the available soil datasets. The 'solvigne' file served as our baseline, chosen for its representation of vineyard soils, and its values closely matched those identified at the five specific locations in Italy. We then adjusted the values in the new soil files where data was available, specifically for clay content, pH, and albedo. For the remaining parameters, we kept the standard values from 'solvigne'.

Adapted parameters technical file "vigne_tec.xml"

Parameter	Original value	Adapted value
Harvest decision	Water content	Physiological maturity

In the 'vigne_tec.xml' technical file, we adjusted by setting the harvest criterion to 'physiological maturity' instead of 'water content'. This modification aligns with the harvesting practices of ancient Romans, who traditionally harvested grapes when they reached maturity, they were unable to perform specific water content measurements

Adapted parameters weather stations:

	Original setting climate change	Adapted setting climate change	Original value elevation	Adapted value elevation	Original value altitude of simulation	Adapted value altitude of simulation
Weather station location 1	Yes	No	No	300 meter	No	300 meter
Weather station location 2	Yes	No	No	450 meter	No	450 meter
Weather station location 3	Yes	No	No	200 meter	No	200 meter
Weather station location 4	Yes	No	No	65 meter	No	65 meter
Weather station location 5	Yes	No	No	100 meter	No	100 meter

"climvigj_sta.xml" was used as a baseline and adapted to represent each of the locations. Climate change was set to 'no' and climate at elevation was set to 'yes'. The elevation for each location was specified.

To run the STICS model for Syrah grapes, we formatted a climate file for each of the years 1850 – 2014. This was done using the CMIP6 climate data. In all climate files, we adapted the CO_2 value to 278, representing the ppm in the atmosphere of the late Holocene (Brovkin et al., 2019). The yields were calculated using no extra irrigation.

To run the USM, we set the USM to 'vine'. The initialization file was set to 'vigne_ini.xml', and the soil file was tailored to match the location of the simulation. Simultaneously, we adjusted the climate station to correspond with the specific location. The USM requires two climate files to be provided. The first climate file was designated as the year before the targeted simulation year. This choice was made to account for Syrah's dormancy period, though it's essential to note that this doesn't impact yields, as dormancy stops at the onset of the simulated year. The second climate file was the target year. We specified the plant year as 'vine_SYRAH_plt.xml' and the technical file as 'vigne_tec.xml'. With these parameters in place, we executed the model to conduct the simulation.

Appendix 5: Temperature threshold for eliminating too-hot spring temperatures

	Maximum average temperature for April + May + June for recent years in degrees C
Wheat 1 spring	20.65
Wheat 2 spring	21.60
Wheat 3 spring	21.88
Wheat 4 spring	22.80
Wheat 5 spring	21.42

	Maximum average temperature for April + May for recent years in degrees C
Grapes 1 spring	19.46
Grapes 2 spring	19.30
Grapes 3 spring	16.30
Grapes 4 spring	20.52
Grapes 5 spring	21.42

	Maximum average temperature for August + September for recent years in degrees C
Grapes 1 summer	24.78
Grapes 2 summer	27.29
Grapes 3 summer	22.19
Grapes 4 summer	27.15
Grapes 5 summer	27.03

Source: (*Weather and Climate Italy*, 2024)

Appendix 6: Test runs LINTUL and STICS

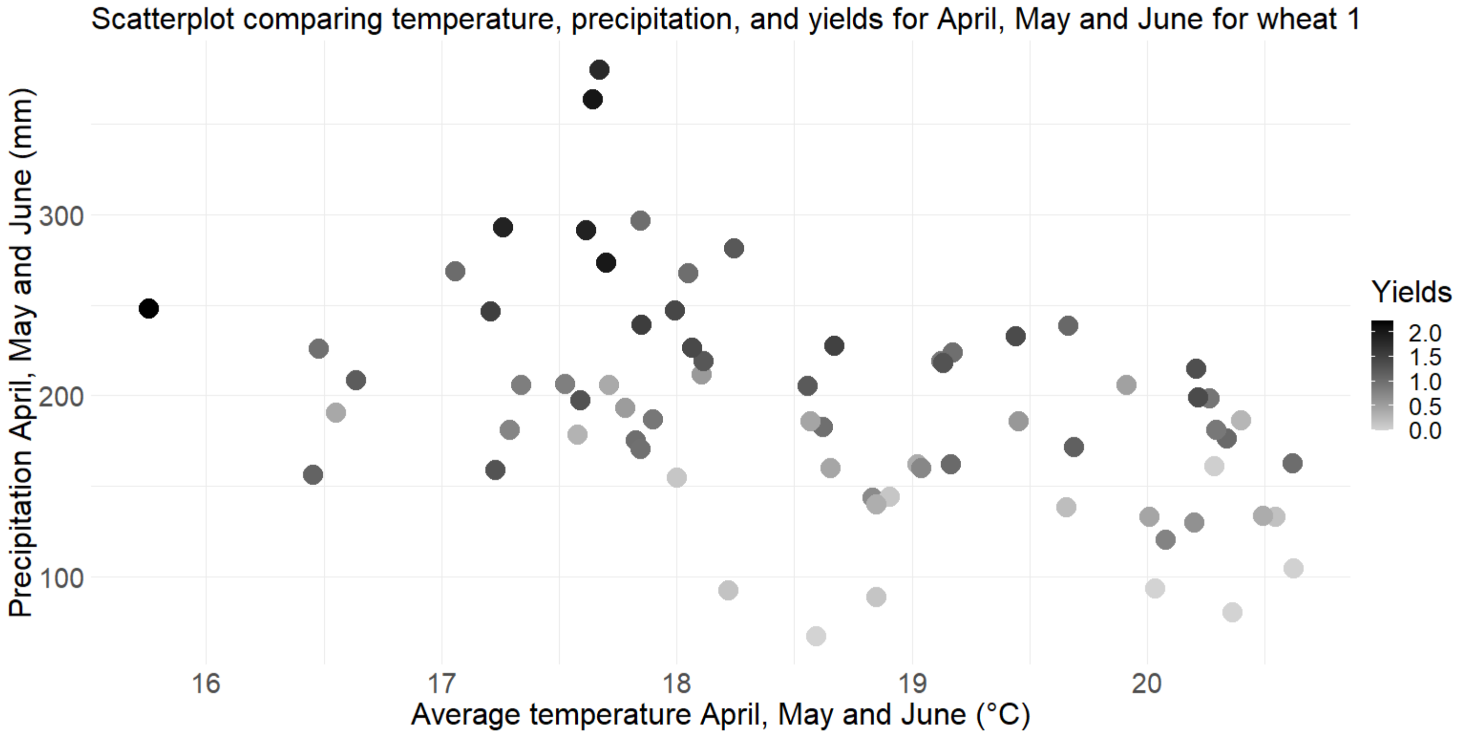
We used static modern climatic data to run the models and test the influence of the variables 'temperature' and 'precipitation'. These are the static variables for both models. The LUE for LINTUL was set to the default for wheat of 3.0.

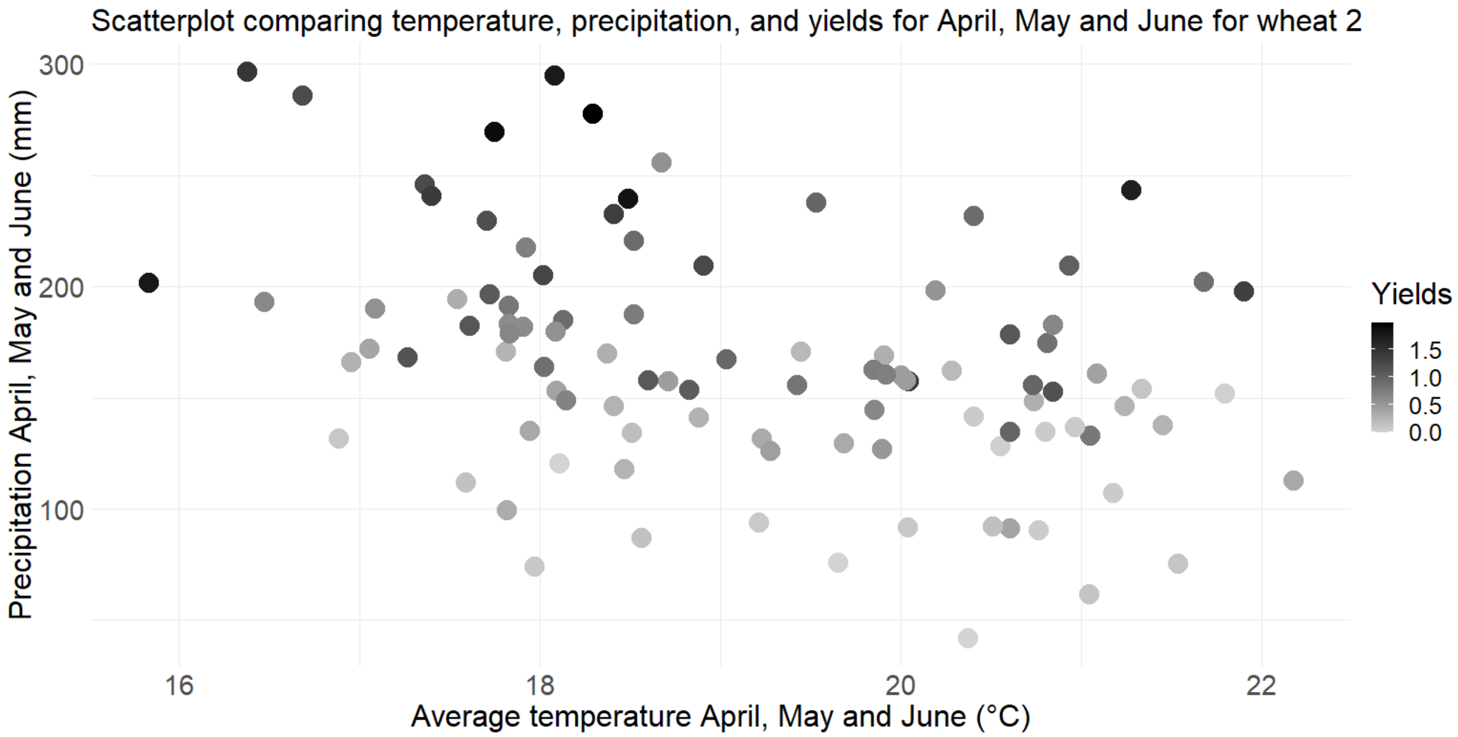
Min and max temp in degrees Celcius per day	18.3
Precipitation in mm per day	1
Vapor pressure in KPascal per day	2.150019
Wind speed in meters/second	4.838803
Solar radiance kJ/m2 per day	20703

Appendix 7: CABO files and LINTUL parameters

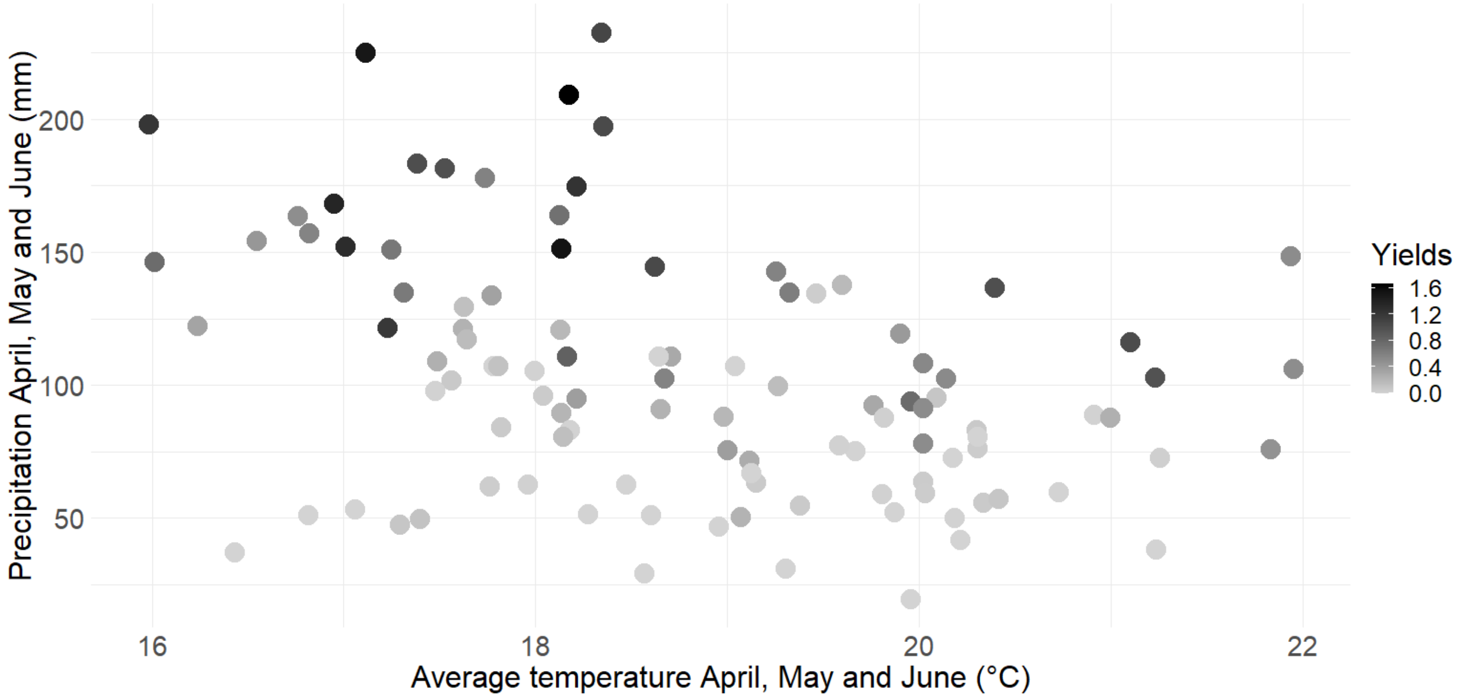
To perform the LINTUL model simulation for five different wheat-growing locations, we modified and combined the climate data from NC files and solar radiation data from a text file to create CABO files. We generated a separate CABO file for each of the five wheat-growing locations. These CABO files contain various parameters such as station number, day, year, daily irradiation (in kJ m^{-2} day^{-1}), minimum temperature (in degrees Celsius), maximum temperature (in degrees Celsius), vapor pressure (in kPa), mean wind speed (in m s^{-1}), and daily precipitation (in mm day^{-1}). The data in each created CABO file spans from January 1, 1850, to December 31, 2014. This data then was split into CABO files per year per location. Since the original datasets often had units that did not align with the requirements of the LINTUL model, we applied necessary unit conversions and modifications. In addition to these data adjustments, certain parameters related to wheat growth and soil characteristics within the LINTUL model were adapted to be representative of wheat growth during Roman times.

Appendix 8: Scatterplot results

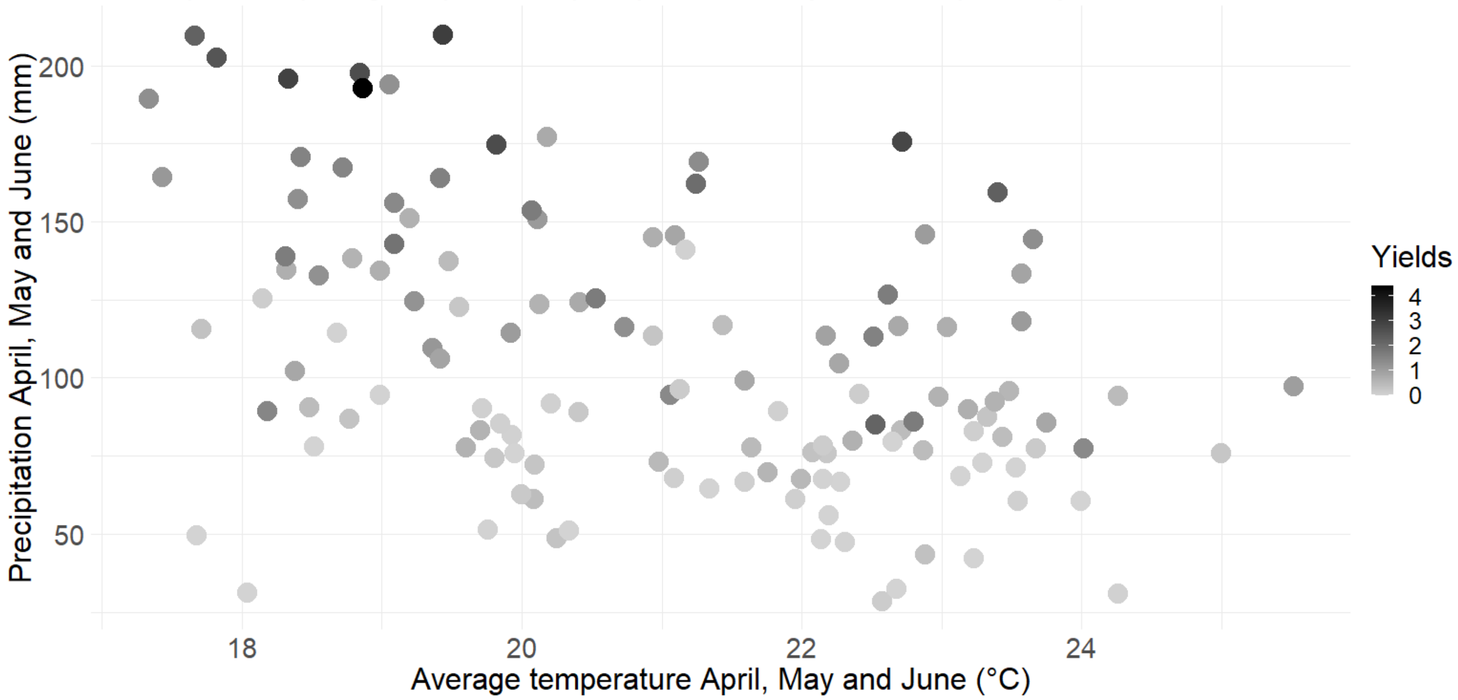


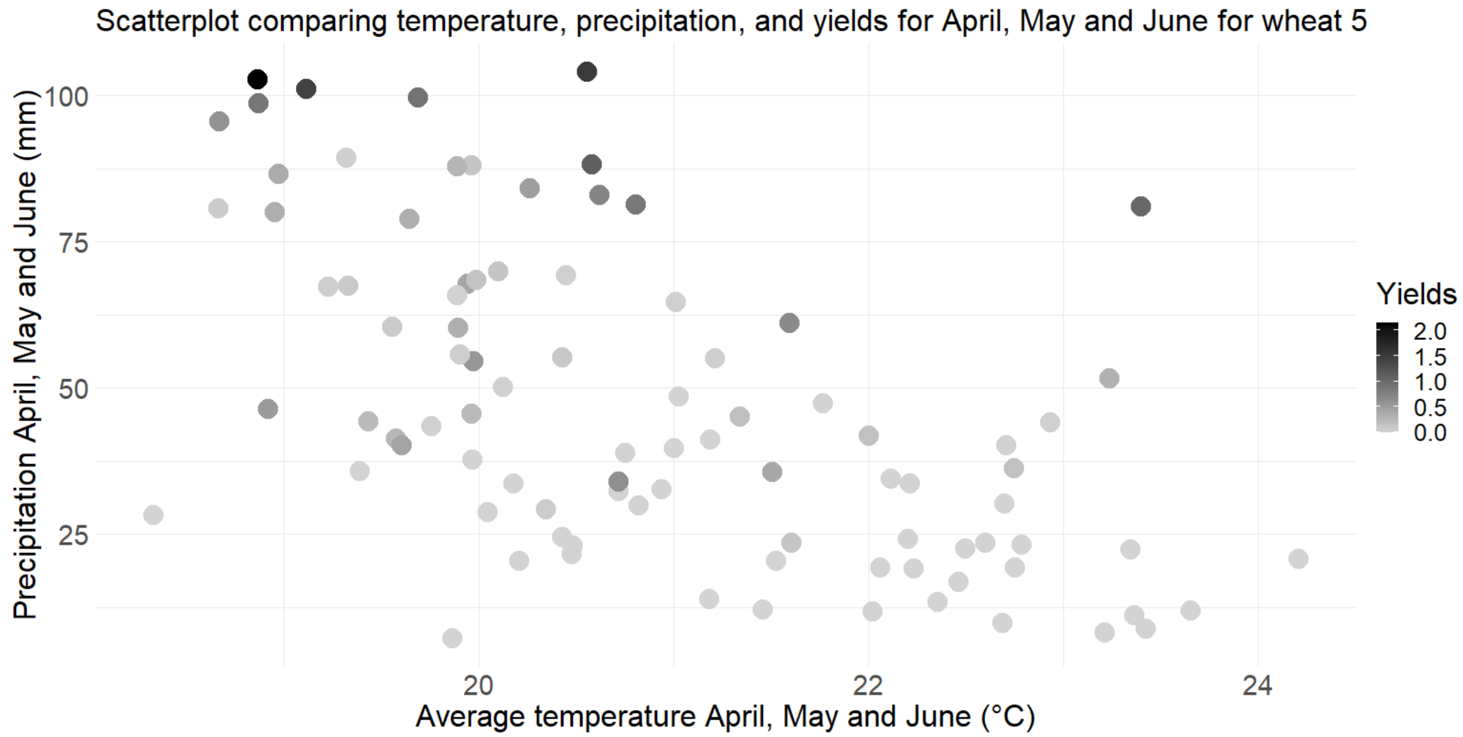


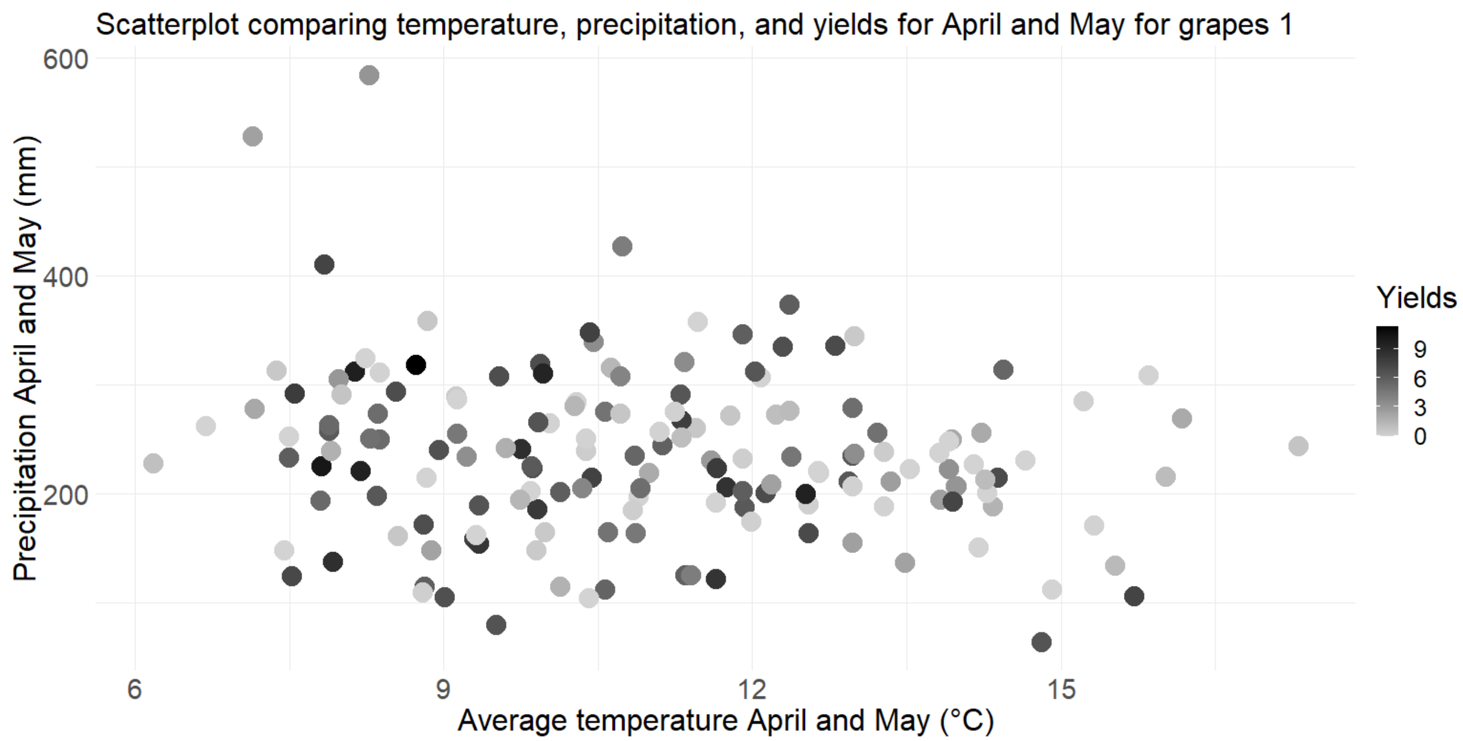
Scatterplot comparing temperature, precipitation, and yields for April, May and June for wheat 3



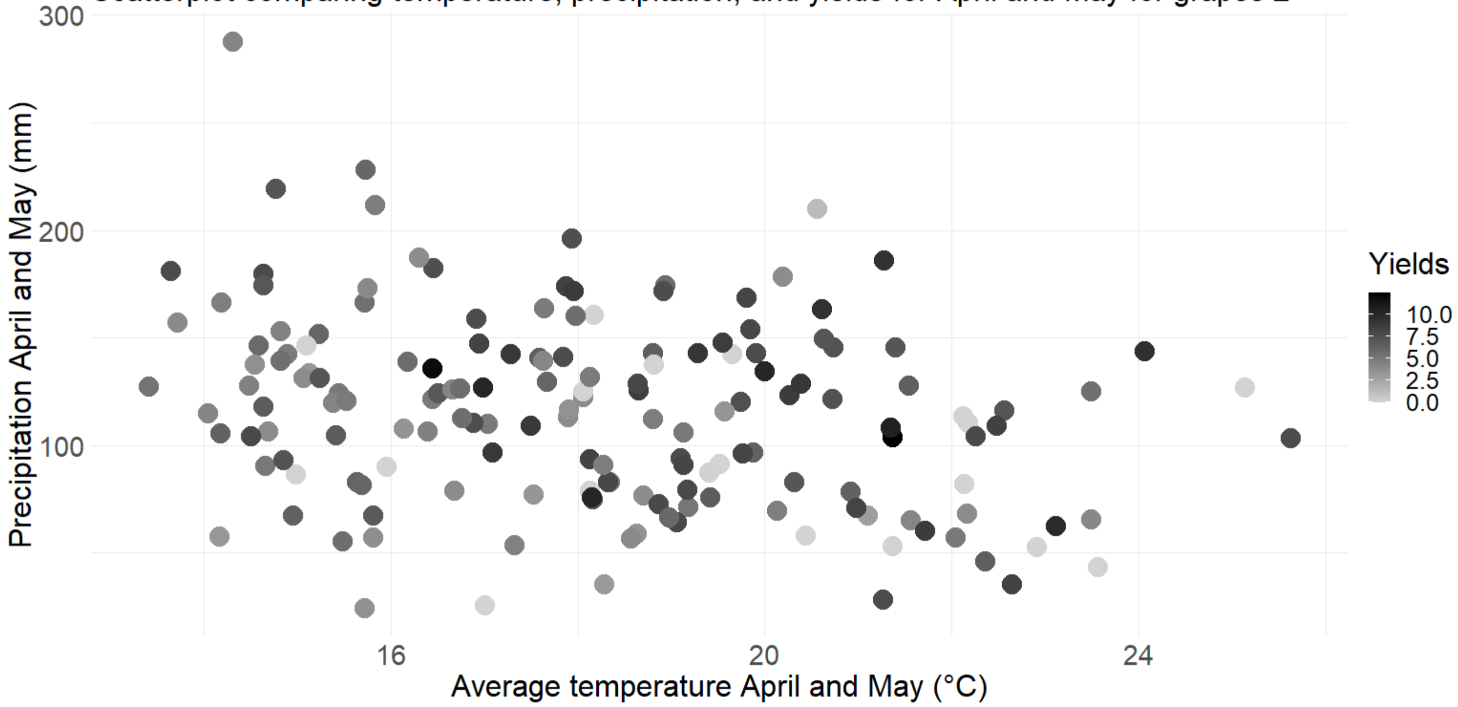
Scatterplot comparing temperature, precipitation, and yields for April, May and June for wheat 4



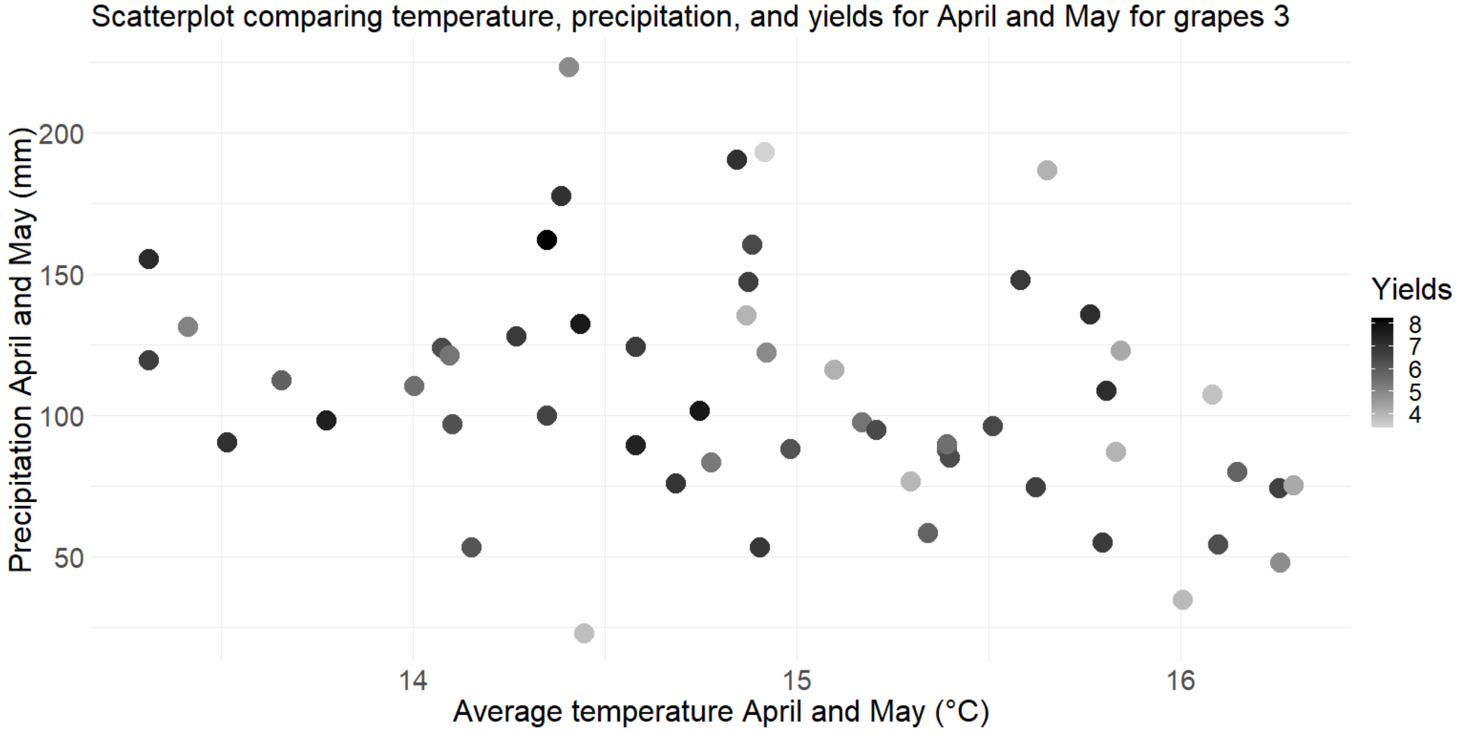

Scatterplot comparing temperature, precipitation, and yields for April, May and June for wheat 5
Precipitation April, May and June (mm)
100
75
50
25
20
22
24
Average temperature April, May and June (°C)
Yields
2.0
1.5
1.0
0.5
0.0


Scatterplot comparing temperature, precipitation, and yields for April and May for grapes 1
Precipitation April and May (mm)
600
400
200
6
9
12
15
Average temperature April and May (°C)
Yields
9
6
3
0

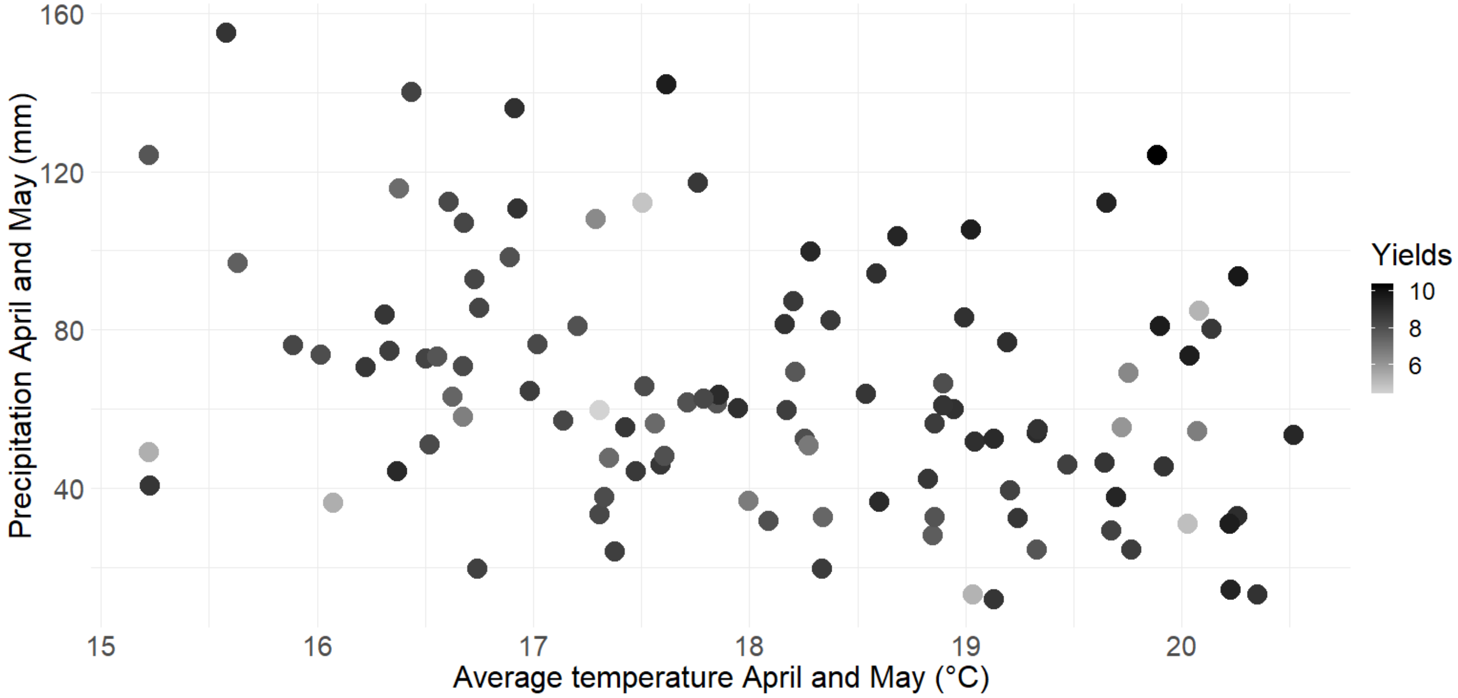
Scatterplot comparing temperature, precipitation, and yields for April and May for grapes 2



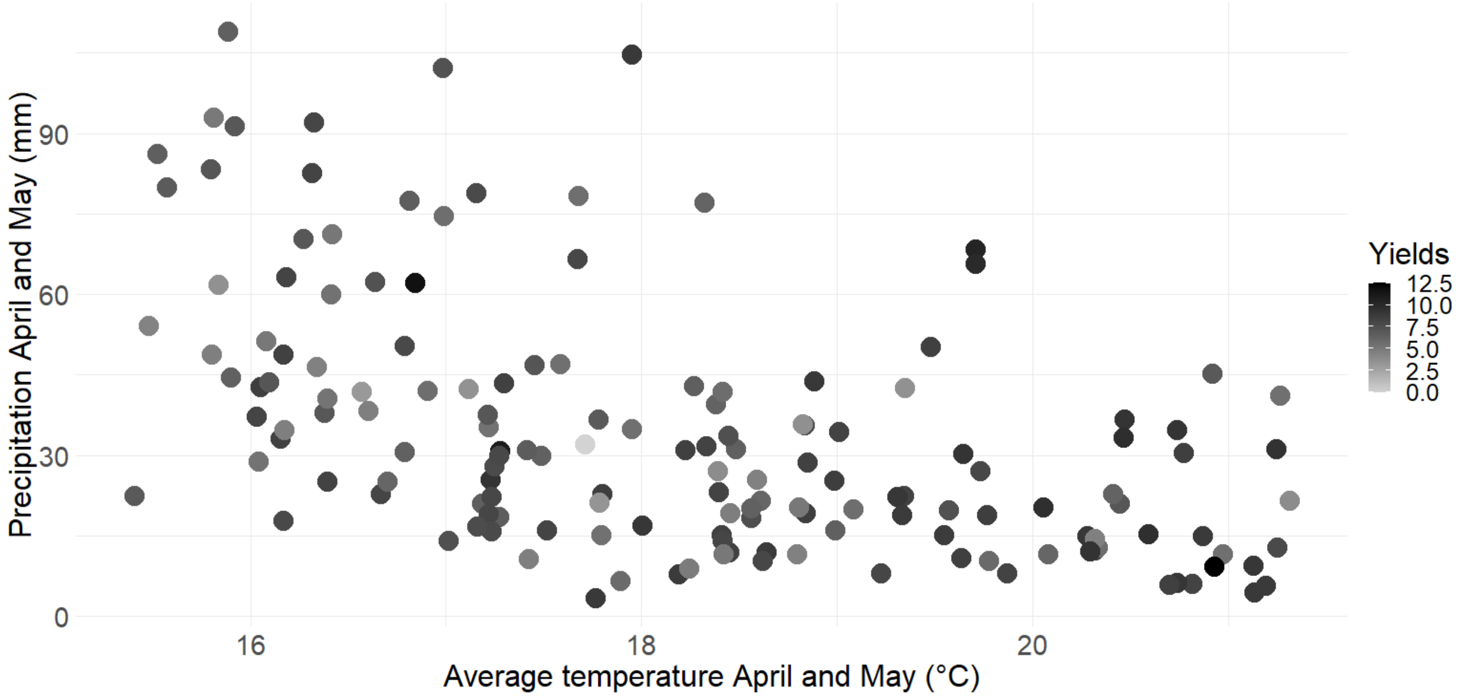
Scatterplot comparing temperature, precipitation, and yields for April and May for grapes 3

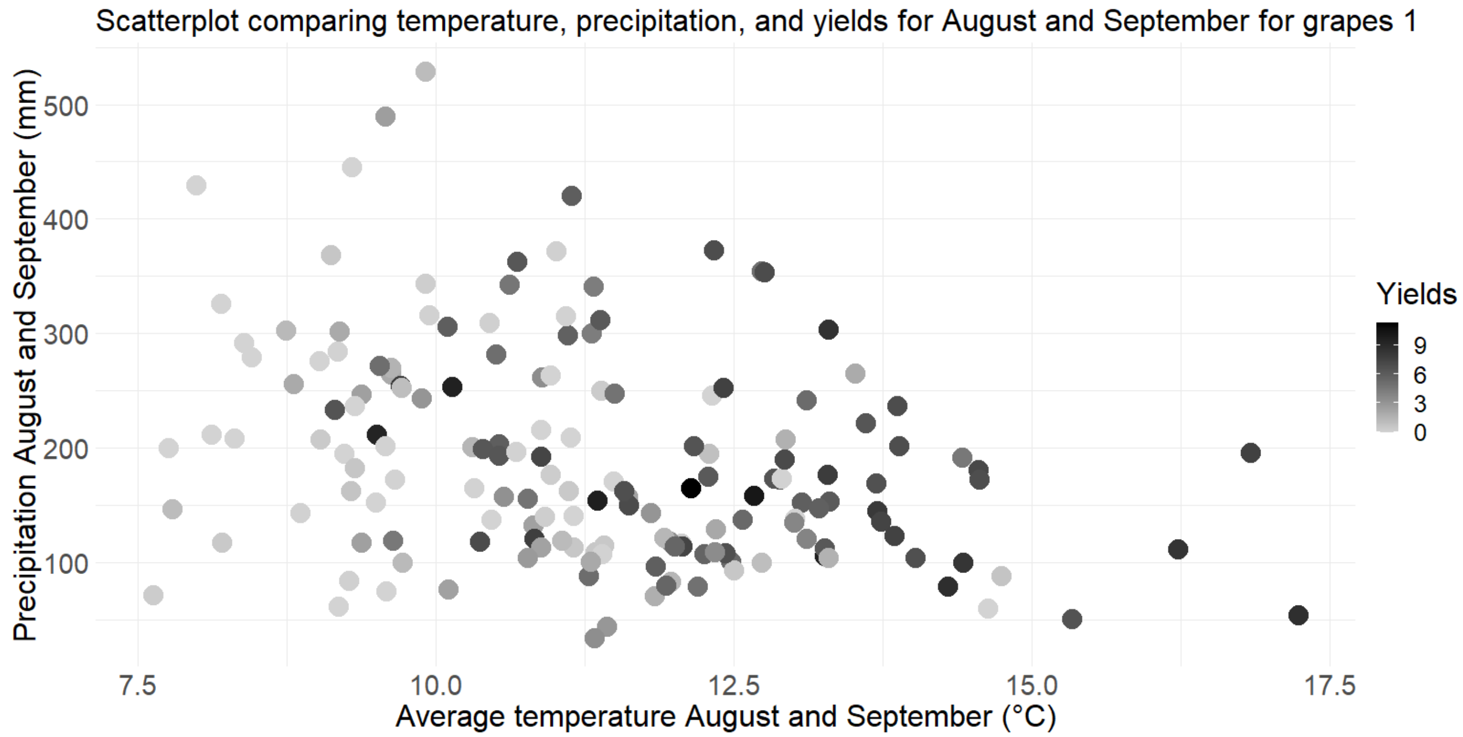


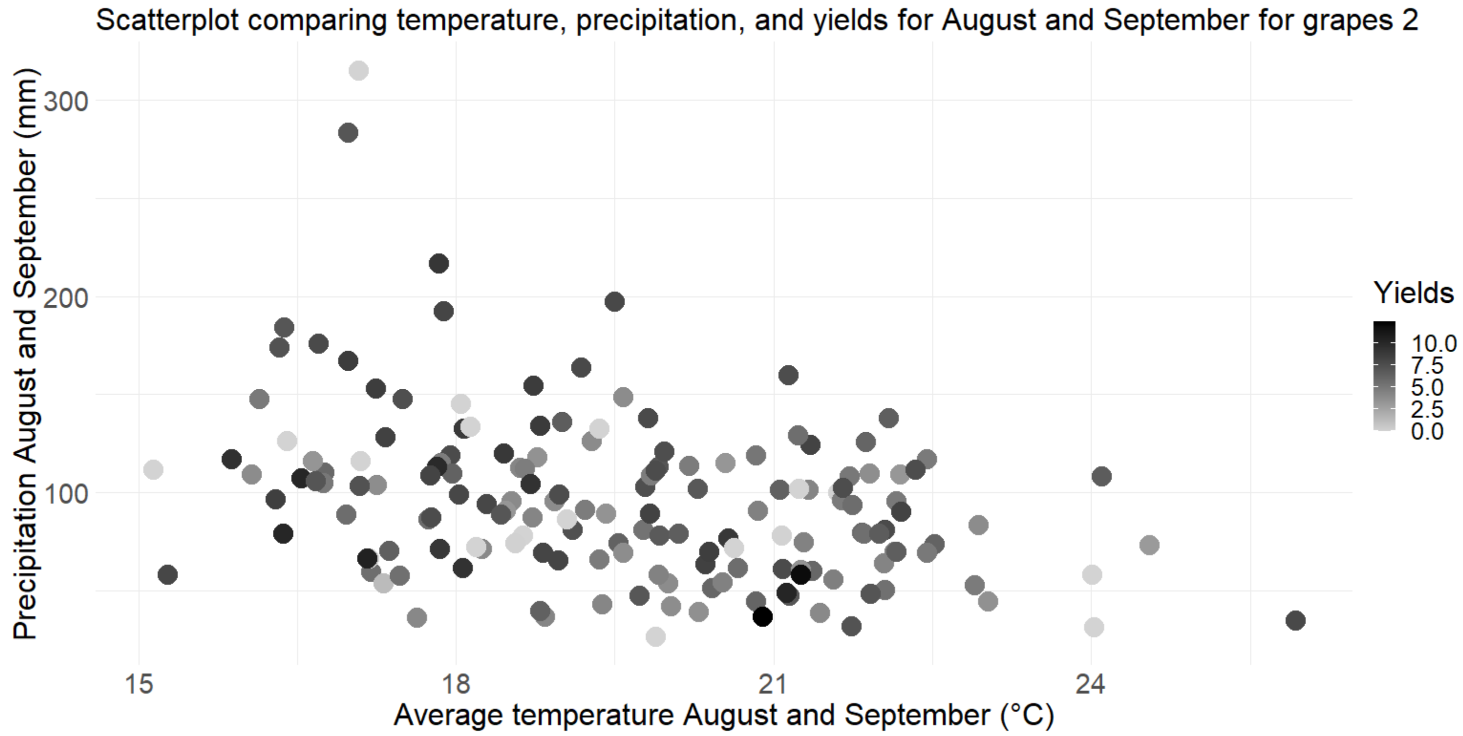
Scatterplot comparing temperature, precipitation, and yields for April and May for grapes 4

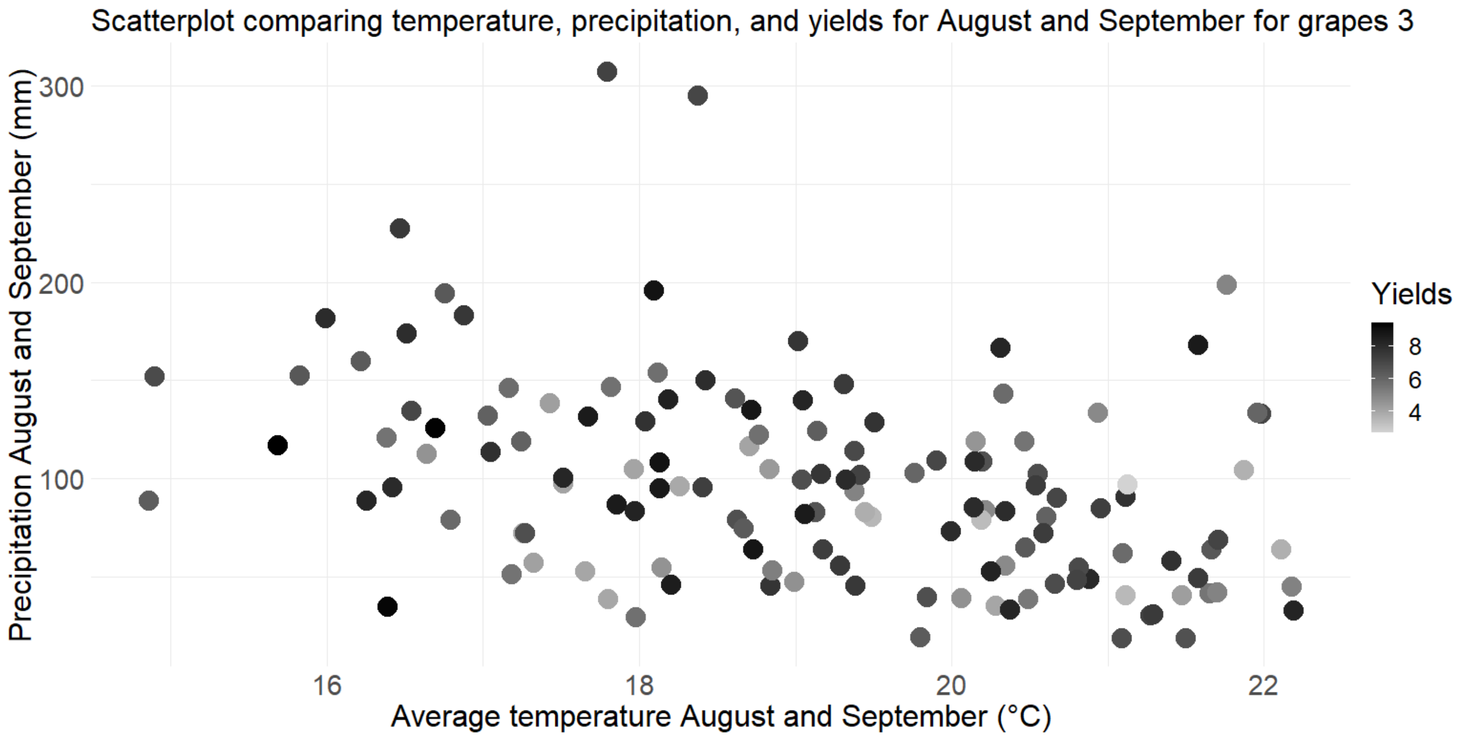


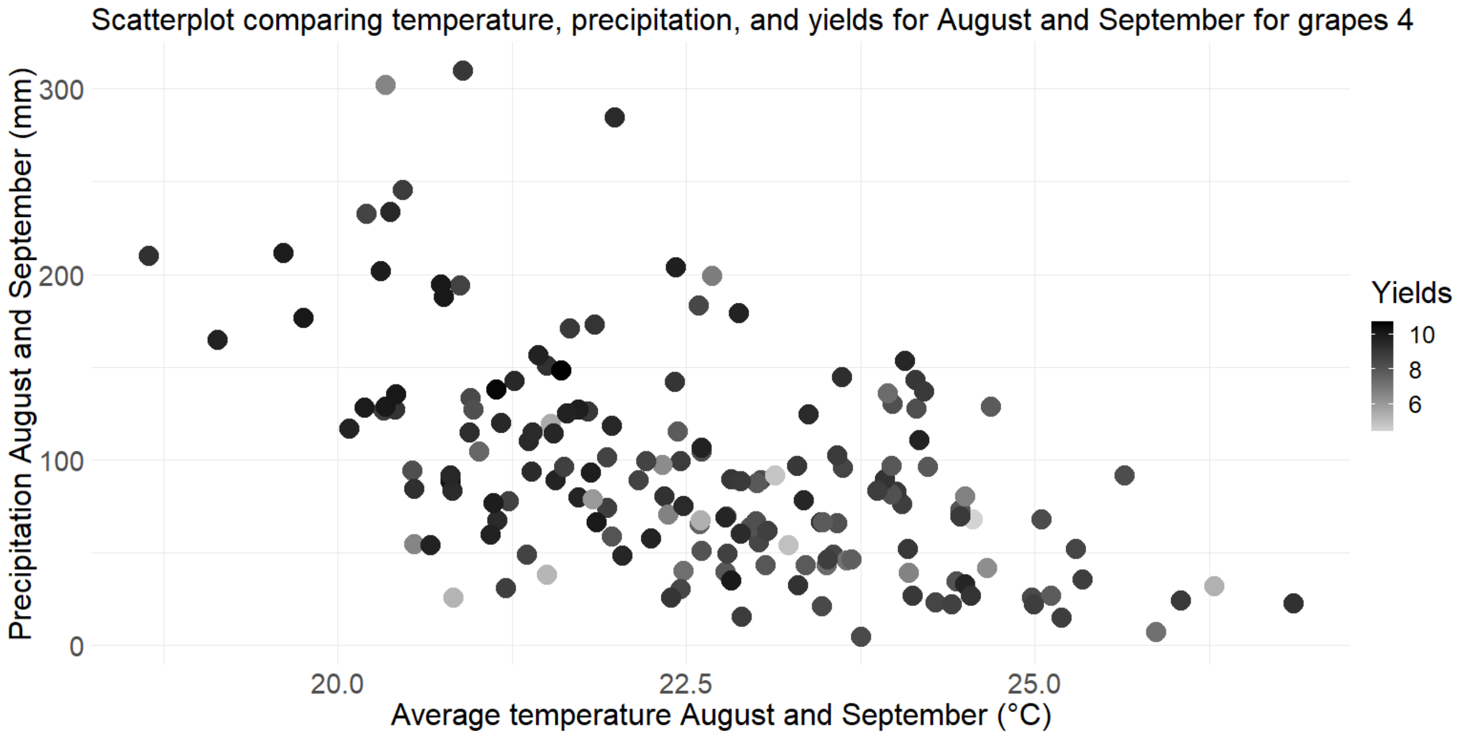
Scatterplot comparing temperature, precipitation, and yields for April and May for grapes 5

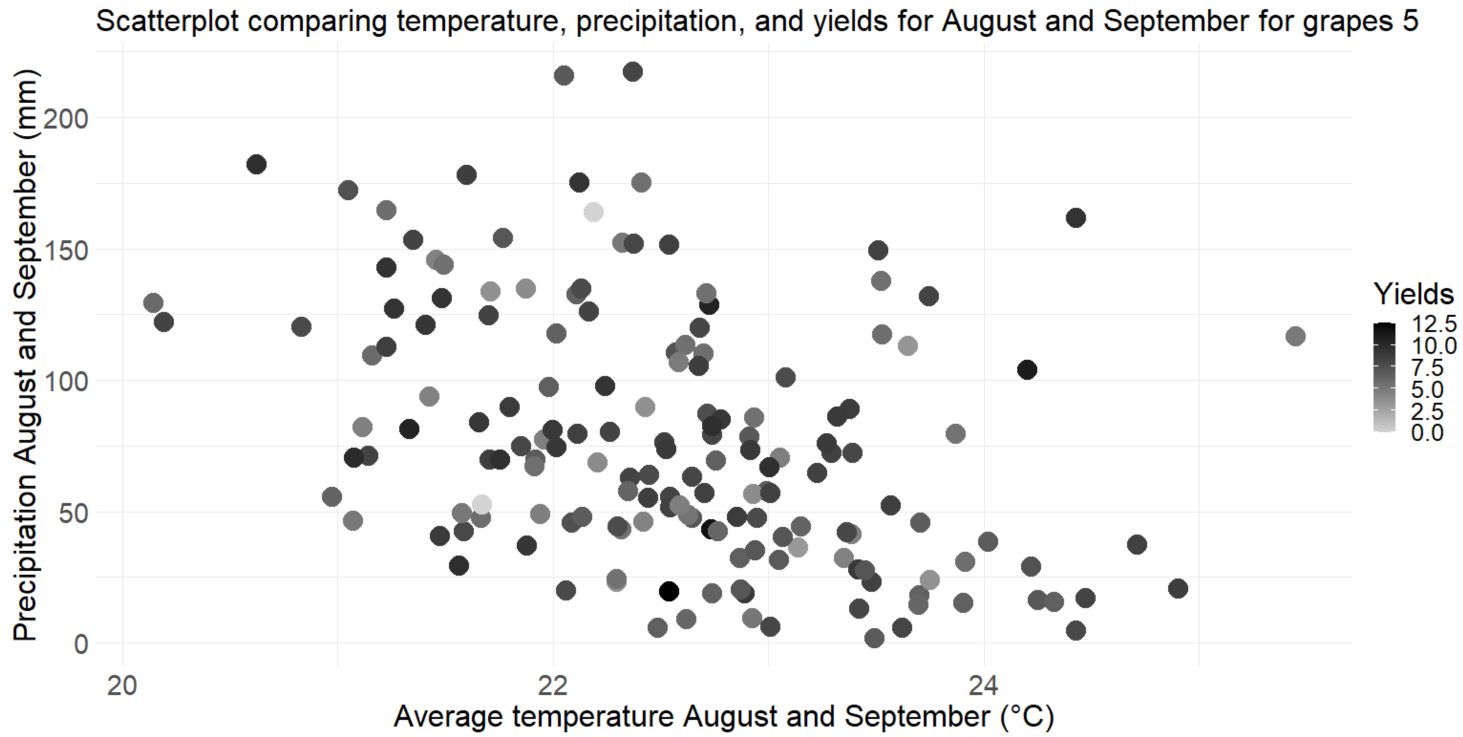



Scatterplot comparing temperature, precipitation, and yields for August and September for grapes 1
Precipitation August and September (mm)
Average temperature August and September (°C)
Yields
7.5
10.0
12.5
15.0
17.5
100
200
300
400
500
0
3
6
9


Scatterplot comparing temperature, precipitation, and yields for August and September for grapes 2
Precipitation August and September (mm)
Average temperature August and September (°C)
Yields
15
18
21
24
100
200
300
0.0
2.5
5.0
7.5
10.0


Scatterplot comparing temperature, precipitation, and yields for August and September for grapes 3
Precipitation August and September (mm)
300
200
100
16
18
20
22
Average temperature August and September (°C)
Yields
8
6
4


Scatterplot comparing temperature, precipitation, and yields for August and September for grapes 4
Precipitation August and September (mm)
300
200
100
0
20.0
22.5
25.0
Average temperature August and September (°C)
Yields
10
8
6



Appendix 9: Conversion factors in grape yields

In this research project, we used conversion factors derived from the Oxford Companion to Wine. Specifically, the following factors, specified for red wine, were used: 100 hectoliters per hectare (hl/ha) is equivalent to 13.7 tons per hectare. 13.7 tons per hectare is equivalent to 5.5 tons per acre (Robinson et al., 2006).

Appendix 10: Z-values linked to Paleo marine core data

Everything below and above the actual values in the dataset is represented by 'below' and 'above'.

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Paleo precipitation values	Below	Below	Below - 5	5 – 13	13 – 22	22 -31	31 – 40	40 – 49	49 – Above	Above	Above	Above
Paleo temperature values in degrees C	21.8 - 22.1	22.1 – 22.4	22.4 – 22.7	22.7 – 22.9	22.9 – 23.2	23.2 – 23.5	23.5 – 23.8	23.8 – 24.0	24.0 – Above	Above	Above	Above

Appendix 11: Precipitation and temperature yield ranges per z-value

Precipitation wheat z-values April, May, and June

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Wheat 1 yields in t/ha	-	0	0.148 0.002 0.131 0	0.018 0.648 0.786	0.121 0.708 0.121 1.296 0.434 0.374 0.208	1.003 0.994 0.771 0.914 0.530 0.981 0.445	0.553 1.228 1.251 0.826 1.307 0.843 0.396	0.988 2.233 1.415 1.528 1.502 1.396 1.075	1.007 1.023 2.018 1.244	1.005 1.880 1.899	-	2.044

					0.751 0.039 1.017	0.576 0.418 0.304 0.276 1.066 0.902 1.161	1.206 0.929 0.919 1.344 1.392 0.484	1.557 0.996 1.439				
Wheat 2 yields in t/ha	-	0 0.125	0.095 0 0.152 0.121	0.144 0.099 0.336 0.085 0.400 0.066 0.068 0.160 0.369	0.179 0.276 0.368 0.341 0.102 0.354 0.001 0.805 0.450 0.516 0.031 0.076 0.978 0.071 0.266	0.281 0.890 1.097 0.277 0.072 0.417 0.698 1.056 0.665 0.460 0.272 0.459 0.308 0.746 0.119 0.726 0.827 0.215 1.424 0.973 0.465 0.419 0.026 1.167	0.278 0.311 1.148 0.578 0.268 0.618 0.622 1.118 0.761 0.392 0.670 0.917 0.311 0.960 0.567 0.226 0.868 0.663 1.111	1.098 0.811 1.295 0.648 1.796 0.326 1.260 0.546 1.034 0.889 1.364	1.367 1.405 0.725 0.925 0.972 1.863 1.198 0.919	0.567 1.242 1.707	1.227 1.912 1.989	1.449 1.768
Wheat 3 yields in t/ha	-	-	0 0 0	0 0 0 0 0.116 0.230 0.091 0 0 04 0 0.066 0 0.065 0	0.011 0.043 0 0.278 0.056 0.062 0 0.380 0.050 0.518 0 0.014 0.016 0.027 0 0 0.048 0.092 0.472	0.066 0.212 0.059 0.234 0.069 08 06 0.141 0.197 0.382 0.159 0.093 0.772 0.069 0.309 0.020 0.520 0 0.010 0.254	1.200 05 0.192 0.854 0.301 0.342 0 0.236 0.253 0.163 0 0.585 0 0.416 0.123 0.547 0.535 0.978 0.511 1.032	0.657 0.137 0.764 0.583 0.354 0.628 0.180 0.040 1.003 1.058	0.726 0.577 0.437 1.309 0.505 0.675 1.378 1.552 0.516	0.994 1.014 0.591 1.242	1.218 1.043 1.665	1.081 1.512
Wheat 4 yields in t/ha	-	-	0 0.137 0 0.039	0 0.308 0.021 0.411 0.330 0 0 0 03 0.078 0.012 0.052 0	0 0.036 0 0.613 0.502 0 0.578 0.219 0.256 0.190 0.478 0.483 0 0.630 0.234 0.014 0.431 0	0.430 1.496 0.054 0.051 0.019 0.212 0.836 0.309 0.058 0.623 2.205 0.107 0.059 1.426 0.811 0.152 1.012 0.848	1.237 1.153 0.115 0.314 0.218 0.617 0.010 0.779 1.695 1.054 0.258 1.323 0.908 0.810 0.408 1.574 0.947 1.068	0.682 0.458 0.599 1.885 0.686 1.282 1.680 0.699 0.853 1.059 0.044 0.907 1.335	1.591 0.647 1.322 1.143 1.525 1.102 1.693 1.443 1.382 2.009 2.290	1.319 0.791 1.554 2.741 2.846	2.950 2.711 2.531 1.280 2.248 3.051 4.420	-

					0.326 0.135 0.070 0.070 0.637 0.417 0.070 0.002 0 0.177 0.432 0 0.252 1.441	0.836 0.446 0.292 0.555 1.694 0.631 0.692	1.671 0.700					
Wheat 5 yields in t/ha	-	-	-	0 0 0 0 0 0 0 0 0 0 0 0 0 0	0 02 0.068 0 0 0 0 0 0 0 0 0 0.009 0.124 0 0 0 0 0	0.232 0.021 02 0.180 0 0.255 0.522 0.639 0.438 0.234 0 0 0 0.008 0.396 0 0.168 0.164 0 0.032 0.017	0.025 0.559 0.047 0.098 04 0.037 0.012 0.312	0.417 0.130 0.333 0.029 0.044 0.148 0.092 0.014 0.083 0.026 0.694	0.370 0.874 0.072 0.337 0.497 0.748 0.343 1.031	0.891 0.128 0.602 0.935 0.275 0.038 1.131	1.535 2.156 1.444	-

Temperature wheat z-values April, May and June

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Wheat 1 yields in t/ha	-	2.233	1.121 0.988 0.418 1.206	0.771 1.023 1.881 0.843 1.296 1.528	0.121 0.826 1.003 1.307 1.005 0.914 1.796 0.530 0.981 0.396 0.304 1.899 2.044 1.557 2.018 1.439	0.553 0 1.228 0.148 1.251 1.007 0.994 1.415 0.445 1.244	0.708 0.121 0.377 1.054 0.360 0.131 0.434 1.502 0.919 0.996 0.751 1.303	0.576 0.208 1.396 1.075 1.161	0.002 0.442 0.648 0.276 0.929 0 1.344 1.066 0.902 0.039 1.392 0.786 0.484	0.018 0.176 0.374 1.017	-	-
Wheat 2 yields in t/ha	-	1.796	1.227 0.102 0.648 1.449	0.279 0.144 1.148 0.578 1.242 1.405 1.118 0.392 0.326	0.311 0.095 1.367 1.098 0.811 0.368 0.890 1.295 0.277 0.268 0.618 0.725	0.179 0.281 0.276 0.567 1.097 0.152 0.761 1.056 1.260 0.961 0.925 0.460 1.863	0 0.341 0.354 0.311 0.665 0.085 0.972 0.450 0.516 0.746 0.226 0.726 0.827	0 0.072 0.099 0.459 0.546 0.400 0.031 0.978 0.160 0.215 1.424 0.919	0.805 0.272 0.066 0.076 0.308 0.119 0.068 0.071 0.125 0.868 0.663 0.973	0.121 0.266 0.369 0.889 0.026 1.364	-	-

L

					0.622 0.417 0.336 0.698 0.670 0.917 0.001 1.768 1.912 0.567 1.198 1.989			0.465 1.111	0.419 1.034 1.707 1.167			
Wheat 3 yields in t/ha	-	0.764 1.218	0 0.342 0.437	0.657 0 1.200 1.014 0 1.512 0.116 0.577 1.309 0.091 0.505 0.675 1.378	0.066 0.011 0.005 0.137 0.994 0.043 0.059 0.591 0.354 0.069 0.008 0 0.236 0.253 0.163 0.123	0.192 0 0 0.212 1.081 0.854 0.301 0 0.726 0.234 0.006 0.141 1.043 1.665 0.585 0 0.382 1.552 1.242 0 1.058	0.583 0.230 0 0 0.197 0.278 0 0.159 0.628 0.062 0 0.380 0.040 0.065	0 0.004 0.056 0.416 0.093 0.180 0.518 0.772 0 0 0.309 0.020 0.547 0.014 0.016 0.535 0 0.520 0.048	0.066 0.050 0.069 0 1.003 0 0 0.092	0.027 0.978 0.010 1.032 0.254 0	0.511 0.516 0.472	-
Wheat 4 yields in t/ha	-	-	0 1.319 2.531 0.314 2.248 1.143 0	0.430 0.682 0 1.496 2.950 2.711 0.115 0.019 0.599 1.322 0.836 0.686 1.554 0.309 1.525 1.282 0.010 1.680 4.420	1.591 0.036 0.054 0.647 0.051 0 0.613 1.237 1.153 0.458 1.280 1.885 0.021 0.218 0.219 2.741 3.051 0.190 1.054 1.443 0.630 0.908	0.791 0.308 0.212 0.411 0.617 0.779 0.256 1.102 1.695 0 0.058 1.693 0.483 0.699 0.258 1.323	0.578 0.478 0.853 0 1.382 0.059 0.070 0.078 0.070 1.426 0.408 0.811 0.152 2.009 0.044	0.502 0 0.330 0 0 0.234 0.014 0.431 0.326 2.205 0.107 0.810 1.059 0.135 0.137 1.574 0 0.637 0.002 0.947 0.012 0.432 0.848 2.846 1.671 1.694	0 0.003 0.623 0.417 0.070 0 0.177 0.052 0.836 0.292 1.068 0.555 0.700 0 0.907 0.631 1.335 2.290 0.692	0.446 0 0.039 1.441	1.012 0.252	-
Wheat 5 yields in t/ha	-	-	0 0.602 0.072	0.232 0.891 0.370 0 0.522 0.044 0.337 2.156 0.092	0.417 0.025 0.021 0.130 0.559 0.128 0.002 0.333 0.935 0.275	0.002 0.068 0 0 0.874 0.029 1.535 0.639 0.098 0	0.180 0 0 0 0.026 0.004 0 0.037 0	0 0 0.168 0 0.012 0 0 0	0 0 0 0.164 0.009 0 0 0.032 0	0.312 0 0 0 0 1.031 0	0	-

LI

				0.038 1.444	0.255 0.047 0 0.148 0 0.438 0.234 0.014 0 0.083 0.343	0.497 08 0 0.748 0 1.131	0 0.694 0.396 0.124		0.017 0			

Precipitation grapes z-values April and May

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Grapes 1 yield in t/ha	-	6.59 6.52	6.79 5.93 0.17 7.48 5.66 1.61 0.02 0.02	7.24 7.66 8.34 8.74 8.43 0 2.35 5.87 4.29 2.52 2.41 0.42 1.23 0.01	6.86 8.11 5.36 0 0.59 6.54 4.57 0.23 0.50 7.09 4.84 0.13 6.25 1.41 1.53 0.15 0 2.52 7.39 0.04 0.03	10.27 5.98 0.90 9.64 0 6.33 3.36 7.57 6.76 6.99 0 6.18 3.85 0 1.96 8.55 5.96 5.96 2.79 5.53 5.10 9.62 0.05 2.47 6.39 4.66	2.01 0.01 3.07 0.22 6.38 3.24 0.01 7.06 0.01 7.99 0.01 1.12 0.09 2.59 1.12 0	0 1.63 6.19 8.76 5.27 4.97 0 5.39 1.75 1.03 0.03 0.60 5.82 7.79 6.70 0.04 0.29 2.06 0.65 4.56 0.05 6.51 4.92 0.35 3.40 0.02 1.00 0.72 0.01 2.02 2.01	9.77 3.49 0.05 11.32 0.55 0 1.35 7.63 3.51 6.93 5.92 7.03 6.84 5.56 6.41 0.48	0.59 0.01 5.99	7.45	4.32
Grapes 2 yields in t/ha	-	3.6 0	3.06 4.46	3.24 3.77 5.64 6.38 7.12 6.79 5.13 10.27 7.91 3.50 7.82 4.02 5.94	6.26 5.01 0 0.04 3.92 6.08 0 7.24 4.77 8.98 3.84 3.30 8.27 7.65 7.88 7.99 8.15 4.74	6.67 4.29 3.87 7.86 6.69 4.32 6.31 4.84 3.89 4.88 3.49 4.52 7.54 5.59 3.54 8.93 4.71 5.04	4.50 4.85 4.99 3.30 5.31 4.95 5.52 3.66 3.89 7.03 12.01 3.88 7.65 6.56 6.50 6.93 8.57 4.27 6.12 5.66 4.21 0	5.82 6.14 4.00 4.44 0 7.64 8.27 0 4.80 5.63 9.08	7.73 4.63 7.48 5.49 7.73 7.00 8.37 4.03 5.72 8.77 7.62	3.80 7.48	7.10 6.04 4.71	-

							0 5.64 4.87 8.96 10.18 7.98					
Grapes 3 yields in t/ha	-	3.83	3.9	6.19 4.89 6.36 5.85 6.83 6.96	3.99 7.00 6.71 5.86 5.35 4.29 6.40 6.71	6.61 5.99 6.51 5.45 6.45 7.58 7.09 6.26 7.83 6.23 7.47 3.76 5.57 4.05	4.12 6.41 6.88 4.94 5.90 6.75 5.54 5.44 6.80 4.29 7.20	7.76 5.13 4.05 6.88 7.18 6.73	8.26 7.26 6.49	7.10 7.13 4.09	3.41	4.91
Grapes 4 yields in t/ha	-	-	8.96 9.44 5.28 8.84	7.64 8.53 8.50 8.59 8.26 8.65 7.90 4.96 8.00 7.86 8.81 9.11 7.36 9.64 8.43	8.80 9.24 8.79 7.22 5.36 8.72 9.21 5.39 8.00 6.74 8.12 8.44 8.89 9.36 8.86 8.81 8.51	6.66 4.45 8.56 8.19 7.25 8.59 7.96 8.97 8.07 7.38 8.80 9.04 7.87 9.19 9.05 8.27 9.21 8.26 9.17 8.63 6.84 8.80 6.04 8.94 6.70 8.87 9.30	8.79 8.42 7.86 8.22 8.55 8.11 8.27 8.13 8.18 7.76 8.08 9.09 9.64 6.40 8.75	8.33 8.35 8.80 8.95 7.95 8.71 9.00 8.99 9.70 8.71 5.24 9.82	6.35 9.39 7.54 8.96 8.32 7.99 9.63 9.26	7.84 7.19 8.23 4.83 8.76 9.45 10.41	9.02 8.42 9.66	8.87
Grapes 5 yields in t/ha	-	-	-	8.99 8.84 8.09 4.90 5.86 8.17 8.35 9.10 8.98 5.89 12.56 9.22 8.33 8.96 8.51	6.56 6.71 7.51 8.16 7.98 8.43 8.06 7.89 9.10 5.69 8.48 7.77 5.46 8.25 8.96 8.50 7.63 8.80 6.17 8.14 5.52 5.08	6.91 8.45 8.20 6.15 9.43 11.05 6.46 8.32 6.42 5.38 6.77 8.58 7.83 3.93 8.45 8.37 6.52 8.54 8.01 7.52 0	3.19 6.44 8.66 5.66 7.08 7.13 4.65 8.18 5.29 4.68 3.59 8.49 5.40 6.91 5.56 7.05 6.31 7.79 6.59 5.71 3.66 3.64	4.57 8.47 7.93 5.06 4.68 4.41 5.57 7.16 8.56	8.29 3.65 5.40 7.37 11.81 8.05 10.42 10.01	7.08 6.63 6.80 5.14 5.64 7.91 6.26 5.61	8.28 6.57 8.16 7.13 6.99	7.40 4.99

					3.39 4.67 9.14 8.69 6.13 5.05 6.45 4.74 4.54 8.85 8.55 8.70 9.12 9.69 9.65 8.94 5.74 4.60 7.45 8.63 3.93 6.48 7.04 7.88 9.40	4.57 9.32 8.36 8.69 8.05 8.60 9.78 9.49 6.35	8.35 9.31 9.04 9.36 6.97 5.57					

Temperature grapes z-values April and May

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Grapes 1 yield in t/ha	-	0.9	5.98 0 0 0 2.11 0.55 2.46	9.77 10.27 7.24 6.92 7.91 1.63 6.19 8.74 5.36 7.45 3.06 5.27 0.05 0.59 4.97 9.64 5.39 2.98 6.33 0.73 0 5.18	6.79 7.66 8.34 5.93 0.17 0.38 6.86 6.59 8.76 0 2.35 6.54 0 11.32 6.87 0.59 3.36 1.75 0 0 1.41 6.70 4.56	3.49 8.11 4.86 4.57 7.57 6.76 5.66 0.03 1.35 1.61 0 7.63 3.94 6.18 6.93 0.03 0.23 0.50 3.85 4.84 1.96 1.42 0.02 5.96 0.29 5.53 4.32 5.10 0.05 9.40 6.51 0.42 0.63	8.43 5.87 6.99 4.29 3.51 6.43 5.92 0.60 5.82 8.55 6.25 7.79 5.96 0.04 2.79 0.65 0.04 0.09 2.47 0.01 6.41 0.22 0.15 0 7.99 1.00	1.03 7.09 7.03 0.13 2.52 1.17 9.62 6.84 0.05 6.39 4.66 0.01 6.38 4.92 0.35 3.40 0.48 5.11 0.09 2.59 5.99 0.03	2.41 2.06 5.56 2.01 1.53 3.07 3.24 0.01 7.06 0.01 0.01 0.02 1.12 0.01 2.52 7.39 0.01 2.02	7.48 0.16 6.52 1.23 0.02 0.04 0	0.02 1.12 2.01	0.72
Grapes 2 yields in t/ha	-	-	3.24 4.29 4.63 5.31 6.31	4.50 4.85 6.67 5.01 7.73 3.87	3.60 6.26 3.77 5.64 4.99 3.30	7.48 0 4.95 3.49 12.01 4.52	0 3.92 4.88 7.64 4.46 8.27	3.06 7.12 0 3.89 8.37 10.27	4.77 7.91 3.84 3.50 6.50 7.82	5.13 7.88 9.08	-	-

			4.00 7.73	5.82 7.86 0.04 5.52 7.10 4.44 6.38 3.66 7.00 7.24 4.26	6.69 4.32 6.08 6.14 5.49 4.84 6.79 3.89 7.03 0 6.04 4.03 4.71	6.93 4.27 5.66 3.80	7.54 5.59 8.98 5.64 8.96 10.18	3.88 7.65 6.56 0 3.30 8.27 6.12 3.54 4.21 8.93 0 4.74 4.87 8.77 4.80 5.63 7.48	8.57 7.65 7.99 8.15 4.02 0 5.72 5.94 4.71 7.62 5.04 7.98			
Grapes 3 yields in t/ha	-	-	7.26 5.90 6.75 5.13 7.09	6.41 7.58 5.54 6.26 5.44	3.83 6.19 6.61 7.76 6.88 8.26 7.10 4.91	7.00 4.94 6.49 5.35 7.13 6.96 6.80 7.83 4.05 7.47 6.73 3.41	3.99 4.12 5.45 5.85 6.45 6.23	5.99 6.51 6.88 6.40 6.71 5.57 4.09	6.36 3.90 5.86 6.83 3.76 4.29 7.18 7.20 4.05	6.71 4.89 4.29	-	-
Grapes 4 yields in t/ha	-	8.80 7.84 5.36	8.87 7.54 8.27	6.66 8.79 9.24 8.19 8.42 7.86 7.38 8.55 8.11 7.19 8.80 8.23 5.39 8.18 8.42 8.32	4.45 8.33 8.59 6.35 8.35 7.22 9.02 8.22 8.53 8.50 8.96 7.95 8.26 8.12 7.99 8.27	7.25 7.96 8.79 8.80 8.72 9.04 8.13 8.00 6.74 7.87 9.66 9.19 4.83 8.76 8.26	8.56 9.39 8.07 9.21 8.95 8.65 8.71 7.76 9.00 8.00 7.36 6.84 8.71 8.80 9.26	8.97 7.64 8.44 7.90 9.05 8.99 7.86 8.08 8.81 9.63 9.21 9.17 9.09 8.63 8.81 5.28 8.84 8.94 8.87	8.59 4.96 8.89 9.36 9.70 9.64 8.86 8.51 9.45 5.24 6.04 6.70 6.40 8.43 8.75 10.41	8.96 9.44 9.11 9.64 9.30 9.82	-	-
Grapes 5 yields in t/ha	-	-	6.91 6.57 6.80 4.41	4.57 6.44 8.66 8.45 8.47 7.08 8.29 8.28 4.99 7.08 8.16 5.06 8.32 7.13 4.68 3.65 7.13 6.99 6.53 7.98 5.40	3.19 5.66 6.56 8.20 6.15 6.71 6.63 7.40 7.93 9.43 11.05 7.51 6.46 8.16 4.65 8.06 7.37 11.81 3.59 7.89 8.49	9.01 6.42 8.99 6.77 5.57 8.58 9.10 7.16 8.84 8.05 6.91 5.46 8.25 5.56 3.39 4.67 5.86 0 5.61	3.93 8.48 8.45 8.96 8.50 7.63 6.31 8.37 6.52 8.54 6.26 7.79 6.17 8.09 8.14 6.59 5.08 4.90 7.52 8.69 5.05	8.43 5.69 8.80 9.14 8.17 9.32 8.85 8.05 3.64 10.42 8.35 8.70 8.56 5.89 7.45 8.63 10.01	6.13 9.31 8.55 9.12 9.69 9.65 5.74 8.33 4.60 9.78 7.04 9.40 6.35	5.52 8.35 9.10 8.60 8.94 8.98 12.56 9.22 3.93 9.36 8.96 8.51 6.97 7.88 9.49 5.57	-	-

				8.18 5.29 5.38 4.68 5.14	7.83 5.40 5.64 7.77 7.05 7.91 8.01		5.71 6.45 4.74 3.66 4.57 8.36 8.69 4.54 9.04 6.48					

Precipitation grapes z-values August and September

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Grapes 1 yield in t/ha	-	-	2.98 3.40	6.59 8.74 8.76 0.73 0 0.59 1.75 5.18 5.92 0 1.42 0.16 2.47 0.01 5.56 4.92 0.35	6.79 8.34 0.17 8.43 5.36 7.45 0 3.06 0.05 0.59 0 9.64 2.11 5.39 6.33 0.55 7.48 2.46 3.36 7.57 6.76 5.66 1.35 1.61 1.03 3.94 3.51 0.03 0.23 3.85 0.60 7.79 2.41 2.79 2.06 4.56 5.53 1.17 7.06 1.23 0.48 2.52 0.09	9.77 10.27 7.24 5.98 7.91 5.93 6.19 8.11 2.35 6.54 5.87 11.32 6.87 0.03 0 6.18 0.50 7.09 4.84 7.03 6.70 0.29 0.65 0.05 0.04 6.84 3.24 0.72 0.01 1.12	7.66 6.92 0 1.63 6.86 0.90 0 4.57 6.43 1.41 0.02 5.96 9.40 6.51 0.42 6.39 0.01 6.41 6.52 0 0.01 7.39 0.02 0.04 0.03	3.49 0.38 5.27 0 4.86 0 7.63 1.96 2.52 5.10 9.62 2.01 1.53 3.07 0.01 7.99 5.11 1.00 0.02 2.01	4.29 5.82 8.55 6.25 0.04 0.09 0.05 0.15 0.01 0.02 2.02 5.99 1.26	4.97 6.99 6.93 0.13 4.32 4.66 0.63 0.22 6.38	5.96	0.01 0
Grapes 2 yields in t/ha	-	-	0 0	3.60 4.85 7.86 6.08 5.49 7.12 3.66 7.03 7.00 7.24 10.27	6.26 4.63 5.64 3.06 4.95 4.32 6.31 7.73 3.89 0	4.50 7.73 3.87 4.99 5.82 5.31 0.04 5.52 6.69 4.00	3.24 6.67 5.01 4.29 3.77 7.48 3.30 0 7.10 6.38 4.84	3.92 6.14 8.27 5.13 7.54 5.59 6.50 7.82 3.54 6.66	3.88 7.65 7.48 8.69 0 4.94 8.64	7.88 7.33 8.70 7.83	7.91 8.11 7.09	9.08

				4.03 4.27 6.12 4.24 6.37 3.80 12.44 4.08	6.56 6.04 3.49 12.01 4.46 4.52 8.37 4.59 3.84 8.57 0 8.15 4.02 4.87 0.12 0.02 8.14 9.39 5.63 0.05 7.98 9.07 6.46 10.57 1.26 5.51	4.44 6.79 3.89 4.26 6.56 8.98 3.50 3.30 8.27 7.99 5.66 0 5.72 5.64 4.80 7.45 7.03 8.31 0 7.70 10.19	0 4.88 7.64 4.71 4.77 7.65 6.93 7.70 4.21 4.74 3.80 10.18 5.94 4.71 3.39 6.34 9.35 9.92 7.62 5.04 7.28 7.98 3.89 0 9.52 0 7.10 8.20 8.53	2.85 8.93 0 7.74 8.96 8.77 0 0 8.39				
Grapes 3 yields in t/ha	-	-	6.83 6.73 6.35	7.26 7.58 5.13 5.54 5.44 6.80 4.05 6.88 4.29 7.74 7.50 5.11 3.50 8.33 4.66 4.00 5.69 8.25 8.61 9.32	4.89 5.85 6.45 8.16 6.96 7.83 7.47 3.76 7.20 6.40 7.15 7.36 4.05 4.66 5.22 7.53 8.91 4.62 8.36 4.18 5.62	7.82 7.10 6.75 4.91 7.43 6.14 3.41 2.74 8.05 7.35 7.44 3.55 8.06 8.03 6.63 8.68 5.88 5.11 3.81 8.69 3.84 8.37 6.78 6.38 6.31 8.75 8.24 8.08 7.35 3.97	6.84 6.71 7.05 5.57 8.10 7.68 3.72 4.54 4.13 4.41 4.10 6.03 7.22 4.09 6.78 6.14 8.11 6.99 5.60 4.61 8.24 5.71 9.02 9.45 7.86	5.86 7.09 4.93 6.05 7.76 6.27 6.20 5.80 8.28 4.25 5.66 8.42 8.85 8.69 6.63 9.41 7.79 7.07	8.30 8.71 7.50 7.68 7.97 6.37 6.91 5.73 6.49	8.97 6.45 7.99 7.62 8.07	5.03	7.54
Grapes 4 yields in t/ha	-	-	7.22 8.42	8.80 8.79 9.24 8.19 8.42 8.59 7.84 8.87 5.36 8.97	6.66 8.56 7.25 6.35 7.38 7.64 8.53 8.55 8.11 7.19	4.45 8.33 9.39 8.79 8.35 8.07 8.22 5.39 8.96 8.18	7.96 7.54 8.59 9.79 8.65 8.99 8.27 8.00 7.86 8.89	7.86 9.04 8.27 8.23 8.96 9.36 9.48 9.64 9.11 7.36	9.09 8.97 9.77 10.13 9.82 9.79	6.84 8.51 9.23 8.67 10.13 9.89 9.98 10.10	9.60 9.94 8.60	8.87

				9.02 8.80 8.72 9.21 8.50 9.66 8.44 9.17 5.28 8.80 9.11 10.07	8.80 8.13 8.00 8.71 7.76 7.99 7.90 4.96 9.00 9.44 8.08 8.76 5.24 9.63 8.65 9.73 6.63 9.76 9.78	8.95 6.74 7.87 8.32 7.95 8.26 9.19 8.12 4.83 9.05 8.81 9.63 9.21 8.26 9.70 8.63 8.81 8.71 9.45 6.04 8.94 6.70 9.74 9.49 10.41 9.93 9.65 9.47 10.08 9.30 9.50 9.94 9.58	8.86 5.54 9.64 6.40 8.63 9.51 9.58 8.75 9.47 9.79 9.72 9.54 9.37	8.84 9.26 8.43 10.63 9.01 9.17 9.92 10.12 9.57 10.04 10.76 9.79 8.24 10.13				
Grapes 5 yields in t/ha	-	-	6.91 7.93	6.44 8.66 8.45 7.08 8.20 8.29 6.15 9.01 7.40 6.57 7.08 8.16 6.46 8.16 3.65 6.42 7.98 3.59 9.10 5.40 7.16 5.14 6.52 6.13 12.56	4.57 3.19 5.66 8.47 6.56 6.71 7.51 7.13 4.68 7.13 4.41 5.40 5.29 4.68 6.77 11.81 7.89 8.84 8.05 6.91 7.77 8.45 7.05 6.31 6.17 5.08 8.01 7.52 5.05 5.71 4.74 8.60 0 9.22 9.78	6.63 4.65 6.80 6.53 8.99 8.06 8.58 8.49 7.83 3.93 8.48 8.25 8.96 8.50 8.37 8.54 6.26 8.14 9.14 8.69 5.61 9.60 8.05 8.56 9.69 8.98 8.33 10.01 6.35 3.95	8.32 6.99 8.18 5.38 5.46 7.63 8.80 6.59 4.67 3.66 9.32 4.54 8.85 9.04 9.10 9.12 9.65 8.94 4.60 8.51 10.49	4.99 11.05 7.37 5.69 5.64 5.56 7.91 7.79 3.39 4.90 5.86 6.45 8.17 8.69 8.63 8.31 9.23	8.28 5.57 4.57 3.64 10.42 8.35 8.35 5.89 3.93 9.36 6.48 5.57 7.88 9.49 5.57 9.40	9.43 5.06 8.43 8.09 0 8.36 8.55 5.74 7.04	5.52 9.31 8.70 7.45 9.70	8.17 6.97

					8.96 6.74							

Temperature grapes z-values August and September

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Grapes 1 yield in t/ha	-	-	0.35 0.01 0.48 0.01 0.00 0.02 0.01 0.02 1.12 0.00	0.00 0.00 2.52 0.65 6.51 0.42 0.16 0.05 0.01 0.63 0.01 2.52 0.72 0.09 0.02 2.02 2.01 1.26	1.41 4.56 0.05 9.40 9.62 0.04 0.09 2.47 0.01 6.39 2.01 1.53 3.07 0.22 7.06 1.23 7.99 5.11 1.12 1.00 0.01 2.59 5.99 0.03	0.00 3.49 0.00 0.59 0.00 0.00 2.46 5.18 4.29 0.23 0.50 0.60 4.84 5.82 0.13 7.79 0.02 5.96 5.96 0.04 0.29 2.41 2.79 2.06 4.32 1.17 5.10 4.66 6.41 6.38 0.15 3.24 3.40 7.39 0.04	9.77 0.17 0.38 7.45 3.06 2.35 2.98 11.32 0.55 4.86 3.36 5.66 1.75 1.35 0.00 0.03 5.92 1.42 7.03 6.25 5.53 6.84 5.56 4.92 6.52	10.27 5.98 5.93 1.63 0.90 5.36 5.27 0.05 4.97 2.11 5.39 6.54 0.59 6.76 0.03 6.99 1.03 0.00 7.63 3.94 3.51 6.18 6.93 3.85 7.09	6.79 6.92 7.91 6.19 6.86 8.11 9.64 5.87 6.33 7.48 7.57 1.61 6.43 1.96 [15] 8.55 6.70	7.24 8.34 8.76 0.73 0.00 4.57 6.87	6.59	7.66 8.43
Grapes 2 yields in t/ha	-	7.98 0.00	7.33 4.94 0.00 7.09 3.89 10.19 9.52 8.53	5.64 3.80 10.18 5.94 3.39 5.63 0.05 6.46 5.04 7.28 8.70 0.00 10.57 1.26 0.00 7.07 7.10 8.39 7.83 8.64 5.51	4.00 3.30 7.99 2.85 4.02 8.93 7.74 5.72 8.96 0.02 4.71 9.39 6.34 8.11 7.03 7.48 9.92 9.08 0.00 0.00 9.07 4.08 7.98 7.70 8.20	3.87 3.92 6.31 4.26 7.91 3.50 4.27 3.54 7.88 6.66 8.15 4.21 0.00 4.74 0.00 4.24 4.87 0.12 8.77 4.80 8.14 7.45 6.37 9.35 7.62 8.69 0.00	7.48 3.30 5.31 7.10 6.08 6.79 3.66 3.89 7.00 4.46 4.52 8.37 4.71 4.77 3.88 6.56 7.54 8.98 3.84 6.93 7.82 8.57 7.70 3.80 8.31 0.00	4.50 4.29 5.64 0.00 0.04 7.73 4.44 6.38 4.84 7.03 0.00 6.04 3.49 12.01 8.27 5.13 10.27 4.59 4.03 7.65 5.59 0.00 6.12 7.65 12.44	3.24 6.26 5.01 7.73 3.77 4.63 4.99 5.82 4.95 5.52 6.69 4.32 6.14 5.49 7.12 7.24 6.56 4.88 7.64 6.50 8.27 5.66	3.60 4.85 3.89	6.67 0.00 3.06 0.00	-

Grapes 3 yields in t/ha	-	6.31 6.91	7.54 8.24 5.60 6.37 8.08 9.32 9.45 8.07 6.49	5.88 6.20 5.80 3.84 6.78 6.14 4.18 6.45 7.99 9.41 4.61 7.62 7.07 7.86 5.62	4.05 4.00 4.13 8.68 4.09 4.25 5.69 4.62 5.66 8.97 8.42 8.37 8.69 8.75 8.61 7.79 8.24 9.02 7.23 5.73	6.75 7.74 6.63 7.68 4.66 5.22 4.41 4.10 6.78 8.69 8.28 8.91 7.97 8.85 6.63 6.38 7.09 5.71 7.35 3.97	7.58 6.80 7.05 3.55 8.06 7.36 7.50 7.76 7.68 6.27 6.35 5.11 6.03 7.53 7.22 3.81 8.11 6.99	4.89 5.86 7.10 8.16 6.96 5.44 4.05 6.84 6.88 4.91 7.20 7.43 6.40 6.14 3.41 8.05 6.71 7.44 5.57 8.30 8.03 4.66 8.10 4.54 8.36 8.25	7.82 7.26 5.85 6.45 6.83 5.54 7.83 7.47 4.29 7.50 5.11 5.03 6.73 3.50 2.74 7.15 7.35 4.93 8.71	5.13 7.09 3.76 6.05 8.33 3.72	-	-
Grapes 4 yields in t/ha	9.23	9.79	10.13 9.72 10.04 9.94 8.60	7.54 8.26 5.28 8.84 8.43 8.87 10.41 9.17 9.60 10.12 6.63 9.76 6.62 9.30 8.67 10.13 9.50 9.98 9.37 9.01 10.10 9.58 8.24 10.13	9.70 5.54 8.71 8.80 9.64 9.45 5.24 9.26 9.51 9.74 9.49 8.75 9.47 8.65 10.63 9.01 8.97 9.92 9.78 9.82 9.54 9.57 9.94 10.76 9.79	7.25 8.50 8.65 7.86 8.08 9.21 9.09 8.86 9.11 8.63 8.81 9.11 6.04 9.63 6.70 6.40 8.63 9.58 9.47 9.93 9.73 9.47 10.08 9.89	8.87 7.64 8.53 8.11 9.21 5.39 8.13 8.00 8.32 7.95 8.26 8.12 8.71 7.99 4.83 7.90 4.96 9.05 8.99 8.27 9.44 8.76 9.63 6.84 8.51 8.94 9.79 9.65 10.07 9.77	6.66 9.39 8.79 7.38 9.02 8.22 8.55 9.04 7.19 8.80 8.23 8.96 8.59 8.18 8.42 7.87 9.19 8.44 7.76 9.00 8.00 8.89 8.81 9.36 9.48 9.64 7.36	4.45 8.19 8.59 6.35 7.96 7.86 8.07 8.72 8.27 8.95 9.79 6.74 9.66 8.96 9.17	8.80 8.79 8.56 8.33 8.42 7.84 8.35 8.80	7.22 5.36 8.97	9.24
Grapes 5 yields in t/ha	5.89 8.31	9.7	7.91 5.08 8.33 4.60 7.45 10.01 6.35	8.01 5.05 5.86 4.57 8.36 4.54 8.70 5.74 8.63 9.78 9.36 8.96 5.57	4.68 6.80 7.98 6.59 4.67 7.52 9.14 8.69 5.71 6.45 5.61 9.60 8.85	6.57 5.06 8.32 3.65 4.41 5.40 8.58 7.83 5.40 7.77 8.25 8.45 8.37	6.56 9.01 6.63 7.08 8.16 7.51 7.13 6.99 6.53 6.42 8.18 5.29 8.99	4.57 6.91 3.19 8.45 8.16 4.65 7.13 4.68 8.06 8.49 9.10 7.16 8.48	6.44 5.66 8.20 6.15 6.71 8.28 6.46 5.38 8.43 5.57 3.59 5.69	7.08 7.40 7.93 9.43 11.05 6.77 6.52	8.47 8.29	8.66

				9.49 9.23 9.40 10.49	8.05 3.64 8.35 9.04 9.10 0.00 9.22 3.93 7.04 6.97	6.26 8.09 5.52 0.00 3.66 9.32 8.35 9.31 8.55 8.56 8.98 12.56 8.17 6.48 8.51 6.74 7.88 3.95	7.37 11.81 7.89 5.14 5.64 8.84 3.93 5.46 5.56 7.05 8.50 7.63 8.54 6.17 8.14 4.90 6.13 4.74 8.17 8.69 10.42 9.12 9.69 9.65 5.57	8.05 6.91 8.96 6.31 8.80 7.79 8.94	3.39 8.60			

Appendix 12: Ranges and averages for wheat and grapes for all z-values, summer and spring

Precipitation wheat z-values April, May, and June

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Range wheat 1 yield t/ha	-	0	0 – 0.148	0.018 – 0.786	0.039 – 1.121	0.276 – 1.161	0.396 – 1.392	0.988 – 2.233	1.007 – 2.018	1.005 – 1.899	-	2.044
Average wheat 1 yield in t/ha	-	0	0.070	0.484	0.537	0.739	0.999	1.413	1.323	1.595	-	2.044
Corresponding precipitation value in mm	13 – 43	43 – 73	73 – 103	103 – 133	133 – 163	163 – 193	193 – 223	223 – 253	253 – 283	283 – 313	313 – 343	343 - 373
Range wheat 2 yields t/ha	-	0 – 0.125	0 – 0.152	0.066 – 0.400	0.001 – 0.978	0.026 – 1.424	0.226 – 1.148	0.326 – 1.796	0.725 – 1.863	0.567 – 1.707	1.227 – 1.989	1.449 – 1.768
Average wheat 2 yield in t/ha	-	0.063	0.092	0.192	0.321	0.586	0.652	1.006	1.172	1.172	1.710	1.609
Corresponding precipitation value in mm	10 – 36	36 – 61	61 – 87	87 – 113	113 – 139	139 – 165	165 – 191	191 – 217	217 – 243	243 – 268	268 – 294	294 - 320
Range wheat 3 yields t/ha	-	-	0	0 - 0.230	0 – 0.518	0 – 0.772	0 – 1.200	0.040 – 1.058	0.437 – 1.552	0.591 – 1.242	1.043 – 1.665	1.081 – 1.512
Average wheat 3 yield in t/ha	-	-	0	0.038	0.109	0.179	0.414	0.540	0.853	0.961	1.309	1.296
Corresponding precipitation value in mm	-34 - -11	-11 – 10	10 – 33	33 – 56	56 – 79	79 – 101	101 – 124	124 – 147	147 – 170	170 – 193	193 – 215	215 - 238
Range wheat 4 yields t/ha	-	-	0 – 0.137	0 – 0.411	0 – 1.441	0.019 – 2.205	0.010 – 1.695	0.044 – 1.885	0.647 – 2.290	0.791 – 2.846	1.280 – 4.420	-
Average wheat 4 yield in t/ha	-	-	0.044	0.093	0.272	0.634	0.843	0.936	1.468	1.850	2.741	-
Corresponding precipitation value in mm	-23 - -1	-1 – 19	19 – 41	41 – 62	62 – 84	84 – 105	105 – 127	127 – 148	148 – 169	169 – 191	191 – 212	212 - 234

Range wheat 5 yields t/ha	-	-	-	0	0 – 0.124	0 – 0.639	0.004 – 0.559	0.014 – 0.694	0.072 – 1.031	0.038 – 1.131	1.444 – 2.156	-
Average wheat 5 yield in t/ha	-	-	-	0	0.011	0.157	0.137	0.183	0.534	0.571	1.712	-
Corresponding precipitation value in mm	-33 - -20	-20 - -7	-7 – 6	6 – 19	19 – 33	33 – 46	46 – 60	60 – 73	73 – 87	87 – 100	100 – 114	114 - 127

Temperature wheat z-values April, May and June

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Range wheat 1 yield t/ha	-	2.233	0.418 – 1.206	0.771 – 1.881	0.121 – 2.044	0 – 1.415	0.121 – 1.502	0.208 – 1.396	0 – 1.392	0.018 – 1.017	-	-
Average wheat 1 yield in t/ha	-	2.233	0.933	1.224	1.134	0.828	0.721	0.883	0.639	0.396	-	-
Corresponding temperature value	14.9 – 15.6	15.6 – 16.2	16.2 – 16.8	16.8 – 17.4	17.4 – 18.0	18.0 – 18.6	18.6 – 19.2	19.2 – 19.9	19.9 – 20.5	20.5 – 21.1	21.1 – 21.7	21.7 – 22.3
Range wheat 2 yields t/ha	-	1.769	0.102 – 1.449	0.144 – 1.405	0.001 – 1.989	0.152 – 1.863	0 – 0.972	0 – 1.424	0.066 – 1.707	0.026 – 1.364	-	-
Average wheat 2 yield in t/ha	-	1.796	0.857	0.737	0.801	0.757	0.478	0.491	0.546	0.506	-	-
Corresponding temperature value	14.7 – 15.4	15.4 – 16.2	16.2 – 16.9	16.9 – 17.7	17.7 – 18.4	18.4 – 19.2	19.2 – 19.9	19.9 – 20.7	20.7 – 21.4	21.4 – 22.2	22.2 – 22.9	22.9 – 23.7
Range wheat 3 yields t/ha	-	0.764 – 1.218	0 – 0.437	0 – 1.512	0 – 0.994	0 – 1.665	0 – 0.628	0 – 0.772	0 – 1.003	0 – 1.032	0.472 – 0.516	-
Average wheat 3 yield in t/ha	-	0.991	0.260	0.695	0.195	0.537	0.187	0.213	0.160	0.383	0.500	-
Corresponding temperature value	14.6 – 15.3	15.3 – 16.0	16.0 – 16.7	16.7 – 17.4	17.4 – 18.1	18.1 – 18.8	18.8 – 19.5	19.5 – 20.2	20.2 – 20.9	20.9 – 21.6	21.6 – 22.3	22.3 – 23.0
Range wheat 4 yields t/ha	-	-	0 – 2.531	0 – 4.420	0 – 3.051	0 – 1.695	0 – 2.009	0 – 2.846	0 – 2.290	0 – 1.441	0.252 – 1.012	-
Average wheat 4 yield in t/ha	-	-	1.079	1.191	0.885	0.668	0.561	0.652	0.560	0.482	0.632	-
Corresponding temperature value	15.1 – 16.1	16.1 – 17.1	17.1- 18.1	18.1 – 19.0	19.0 – 20.0	20.0 – 21.0	21.0 – 22.0	22.0 – 22.9	22.9 – 23.9	23.9 – 24.9	24.9 – 25.9	25.9 – 26.9
Range wheat 5 yields t/ha	-	-	0 – 0.602	0 – 2.156	0 – 0.935	0 – 1.535	0 – 0.694	0 – 0.168	0 – 0.164	0 – 1.031	0	
Average wheat 5 yield in t/ha	-	-	0.225	0.557	0.209	0.352	0.112	0.023	0.020	0.192	0	
Corresponding temperature value	16.7 – 17.4	17.4 – 18.1	18.1 – 18.8	18.8 – 19.5	19.5 – 20.2	20.2 – 20.9	20.9 – 21.6	21.6 – 22.3	22.3 – 23.0	23.0 – 23.7	23.7 – 24.4	24.4 – 25.1

Precipitation grape z-values April and May

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Range grape 1 yield t/ha	-	6.52 – 6.59	0.02 – 7.48	0 – 8.74	0 – 8.11	0 – 10.27	0 – 8.76	0 - 9.40	0 – 11.32	0.01 – 5.99	7.45	4.32
Average grape 1 yield in t/ha	-	6.56	3.46	4.25	3.05	3.85	2.73	3.02	4.80	2.20	7.45	4.32

Corresponding precipitation value	7 – 45	45 – 83	83 – 121	121 – 159	159 – 197	197 – 235	235 – 272	272 – 310	310 – 348	348 – 386	386 – 424	424 - 462
Range grape 2 yields t/ha	-	0 – 3.60	3.06 – 4.46	3.24 – 10.27	0 – 8.98	3.49 – 8.83	0 – 12.01	0 – 9.08	4.03 – 8.77	3.80 – 7.48	4.71 – 7.10	-
Average grape 2 yields in t/ha	-	1.80	3.76	5.96	5.23	5.39	5.64	5.07	6.78	5.64	5.95	-
Corresponding precipitation value	-12 – 10	10 – 32	32 – 54	54 – 76	76 – 98	98 – 120	120 – 143	143 – 165	165 – 187	187 – 209	209 – 231	231 - 253
Range grape 3 yields t/ha	-	3.83	3.90	4.89 – 6.96	3.99 – 7.00	3.76 – 7.83	4.12 – 7.20	4.05 – 7.76	6.49 – 8.26	4.09 – 7.13	3.41	4.91
Average grape 3 yields in t/ha	-	3.83	3.90	6.18	5.79	6.20	5.84	6.29	7.34	6.11	3.41	4.91
Corresponding precipitation value	-17 – 3	3 – 24	24 – 44	44 – 65	65 – 86	86 – 107	107 – 128	128 - 149	149 – 170	170 – 191	191 – 212	212 - 233
Range grape 4 yields t/ha	-	-	5.28 - 9.44	4.96 - 9.64	5.36 – 9.36	4.45 – 9.30	6.40 – 9.64	5.24 – 9.82	6.35 – 9.63	4.83 – 10.41	8.42 – 9.66	8.87
Average grape 4 yield in t/ha	-	-	8.13	8.15	8.15	8.11	8.28	8.55	8.43	8.10	9.03	8.87
Corresponding precipitation value	-28 - -12	-12 – 3	3 – 18	18 – 34	34 – 49	49 – 65	65 – 80	80 – 96	96 – 111	111 – 127	127 – 142	142 - 158
Range grape 5 yields t/ha	-	-	-	4.90 – 12.56	3.39 – 9.69	0 – 11.05	3.19 – 9.36	4.41 – 8.56	3.65 – 11.81	5.14 – 7.91	6.57 – 8.28	4.99 – 7.40-
Average grape 5 yield in t/ha	-	-	-	8.32	7.28	7.48	6.44	6.27	8.13	6.38	7.43	6.20
Corresponding precipitation value	-36 - -24	-24 - -12	-12 - -1	-1 – 10	10 – 22	22 – 34	34 – 45	45 – 57	57 – 69	69 – 81	81 – 92	92 - 104

Temperature grape z-values April and May

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Range grape 1 yield t/ha	-	0.90	0 – 5.98	0 – 10.27	0 – 11.32	0 – 9.40	0 – 8.55	0.01 – 9.62	0.01 – 7.39	0 – 7.48	0.02 – 2.01	0.72
Average grape 1 yield in t/ha	-	0.90	1.59	5.26	4.21	3.63	3.78	3.45	2.23	2.21	1.05	0.72
Corresponding temperature value	4.0 – 5.1	5.1 – 6.3	6.3 – 7.5	7.5 – 8.7	8.7 – 9.8	9.8 – 11.0	11.0 – 12.2	12.2 – 13.4	13.4 – 14.5	14.5 – 15.7	15.7 – 16.9	16.9 – 18.1
Range grape 2 yields t/ha	-	-	3.24 – 7.73	0.04 – 7.86	0 – 7.03	0 – 12.01	0 – 10.18	0 – 10.27	0 – 8.57	5.13 – 9.08	-	-
Average grape 2 yields in t/ha	-	-	5.07	5.41	4.93	5.31	6.34	5.28	5.99	7.36	-	-
Corresponding temperature value	11.7 – 12.6	12.6 – 13.4	13.4 – 14.2	14.2 – 15.0	15.0 – 15.8	15.8 – 16.7	16.7 – 17.5	17.5 – 18.3	18.3 – 19.1	19.1 – 20.0	20.0 – 20.8	20.8 – 21.6
Range grape 3 yields t/ha	-	-	5.13 – 7.26	5.44 – 7.58	3.83 – 8.26	3.41 – 7.83	3.99 – 6.45	4.09 – 6.88	3.76 – 7.20	4.29 – 6.71	-	-
Average grape 3 yields in t/ha	-	-	6.43	6.25	6.44	6.18	5.35	6.02	5.49	5.30	-	-
Corresponding temperature value	12.5 – 12.9	12.9 – 13.3	13.3 – 13.7	13.7 – 14.1	14.1 – 14.5	14.5 – 14.9	14.9 – 15.3	15.3 – 15.8	15.8 – 16.2	16.2 – 16.6	16.6 – 16.9	16.9 – 17.4
Range grape 4 yields t/ha	-	5.36 – 8.80	7.54 – 8.87	5.39 – 9.24	4.45 – 9.02	4.83 – 9.66	6.84 – 9.39	5.28 – 9.63	4.96 – 10.41	8.96 – 9.82	-	-
Average grape 4 yield in t/ha	-	7.33	8.23	7.98	7.94	8.13	8.48	8.54	8.12	9.38	-	-
Corresponding temperature value	13.9 – 14.6	14.6 – 15.3	15.3 – 16.0	16.0 – 16.7	16.7 – 17.4	17.4 – 18.1	18.1 – 18.8	18.8 – 19.5	19.5 – 20.1	20.1 – 20.8	20.8 – 21.5	21.5 – 22.2
Range grape 5 yields t/ha	-	-	4.41 – 6.91	3.65 – 8.66	3.19 – 11.81	0 – 9.10	3.66 – 9.04	3.64 – 10.42	4.60 – 9.78	3.93 – 12.56	-	-

Average grape 5 yield in t/ha	-	-	6.17	6.62	7.23	6.54	6.85	8.12	7.98	8.25	-	-
Corresponding temperature value	13.3 – 14.1	14.1 – 14.9	14.9 – 15.7	15.7 – 16.6	16.6 – 17.4	17.4 – 18.2	18.2 – 19.0	19.0 – 19.8	19.8 – 20.6	20.6 – 21.4	21.4 – 22.3	22.3 – 23.1

Precipitation grape z-values August and September

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Range grape 1 yield t/ha	-	-	2.98 – 3.40	0 – 8.76	0 – 9.64	0 – 11.32	0 – 9.40	0 – 9.62	0.01 – 8.55	0.13 – 6.99	5.96	0 – 0.01
Average grape 1 yield in t/ha	-	-	3.19	3.13	3.52	4.66	3.42	3.18	2.66	3.91	5.96	0.005
Corresponding precipitation value	-92 - -45	-45 – 2	2 – 49	49 – 96	96 – 143	143 – 190	190 – 237	237 – 284	284 – 331	331 – 378	378 – 425	425 – 472
Range grape 2 yields t/ha	-	-	0	3.60 – 12.44	0 – 12.01	0 – 10.19	0 – 10.18	0 – 8.96	0 – 8.69	7.33 – 8.70	7.09 – 8.11	9.08
Average grape 2 yields in t/ha	-	-	0	6.08	5.29	5.45	5.60	5.62	5.90	7.94	7.70	9.08
Corresponding precipitation value	-33 - -11	-11 – 10	10 – 32	32 – 53	53 – 74	74 – 96	96 – 117	117 – 139	139 – 160	160 – 182	182 – 203	203 - 225
Range grape 3 yields t/ha	-	-	6.35 – 6.83	3.50 – 9.32	3.76 – 8.91	2.74 – 8.75	3.72 – 6.45	4.25 – 9.41	5.73 – 8.71	6.45 – 8.97	5.03	7.54
Average grape 3 yields in t/ha	-	-	6.64	6.28	6.32	6.52	6.35	6.95	7.30	7.82	5.03	7.54
Corresponding precipitation value	-55 - -29	-29 - -4	-4 – 21	21 – 47	47 – 72	72 – 97	97 – 123	123 – 148	148 – 173	173 – 199	199 – 224	224 - 249
Range grape 4 yields t/ha	-	-	7.22 – 8.42	5.28 – 10.07	4.96 – 9.78	4.45 – 10.41	5.54 – 9.79	7.36 – 10.76	8.97 – 10.13	6.84 – 10.13	8.60 – 9.94	8.87
Average grape 4 yield in t/ha	-	-	7.82	8.54	8.04	8.54	8.67	9.22	9.60	9.17	9.38	8.87
Corresponding precipitation value	-80 - -51	-51 - -22	-22 – 7	7 – 37	37 – 66	66 – 95	95 – 124	124 – 153	153 – 182	182 – 212	212 – 241	241 - 270
Range grape 5 yields t/ha	-	-	6.91 – 7.93	6.59 – 12.56	0 – 11.81	3.93 – 10.01	3.66 – 10.49	3.39 – 11.05	3.64 – 10.42	0 – 9.43	5.52 – 9.70	6.97-8.17
Average grape 5 yield in t/ha	-	-	7.42	7.19	6.67	7.77	7.51	7.04	7.05	6.74	8.14	7.57
Corresponding precipitation value	-66 - -42	-42 - -18	-18 – 5	5 – 29	29 – 53	53 – 77	77 – 101	101 – 125	125 – 148	148 – 172	172 – 196	196 - 220

Temperature grape z-values August and September

	-3 to -2.5	-2.5 to -2	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3
Range grape 1 yield t/ha	-	-	0 – 1.12	0 – 6.15	0.01 – 9.62	0 – 7.79	0 – 11.32	0 – 10.27	1.61 – 9.64	0 – 8.76	6.59	7.66 – 8.43
Average grape 1 yield in t/ha	-	-	0.20	1.09	3.04	2.79	4.20	4.36	6.56	5.22	6.59	8.43
Corresponding temperature value	5.75 – 6.68	6.68 – 7.61	7.61 – 8.55	8.55 – 9.48	9.48 – 10.41	10.41 – 11.34	11.34 – 12.27	12.27 – 13.20	13.20 – 14.14	14.14 – 15.07	15.07 – 16.00	16.00 – 16.93
Range grape 2 yields t/ha	-	0 – 7.89	0 – 10.19	0 – 10.57	0 – 9.92	0 – 9.35	0 – 8.98	0 - 12.44	3.24 – 8.27	3.60 – 4.85	0 – 6.67	-
Average grape 2 yields in t/ha	-	3.99	6.44	5.64	6.10	5.17	5.82	5.53	5.84	4.11	2.43	-

Corresponding temperature value	13.31 – 14.35	14.35 – 15.39	15.39 – 16.44	16.44 – 17.48	17.48 – 18.52	18.52 – 19.57	19.57 – 20.61	20.61 – 21.65	21.65 – 22.70	22.70 – 23.74	23.74 – 24.78	24.78 – 25.82
Range grape 3 yields t/ha	-	6.31 – 6.91	5.60 – 9.45	3.84 – 9.41	4.00 – 9.02	3.97 – 8.91	3.55 – 8.11	3.41 – 8.36	2.74 – 8.71	3.72 – 8.33	-	-
Average grape 3 yields in t/ha	-	6.61	7.68	6.36	6.75	6.69	6.71	6.53	6.22	5.68	-	-
Corresponding temperature value	13.83 – 14.71	14.71 – 15.60	15.60 – 16.48	16.48 – 17.36	17.36 – 18.25	18.25 – 19.13	19.13 – 20.01	20.01 – 20.90	20.90 – 21.78	21.78 – 22.66	22.66 – 23.54	23.54 – 24.43
Range grape 4 yields t/ha	9.23	9.79	8.60 – 10.13	5.28 – 10.41	5.24 – 10.76	6.04 – 10.08	4.83 – 10.07	6.66 – 9.64	4.45 – 9.79	7.84 – 8.80	5.36 – 8.97	9.24
Average grape 4 yield in t/ha	9.23	9.76	9.69	8.90	9.19	8.70	8.29	8.49	8.12	8.49	7.18	9.24
Corresponding temperature value	17.89 – 18.68	18.68 – 19.46	19.46 – 20.24	20.24 – 21.02	21.02 – 21.80	21.80 – 22.58	22.58 – 23.36	23.36 – 24.15	24.15 – 24.93	24.93 – 25.71	25.71 – 26.49	26.49 – 27.27
Range grape 5 yields t/ha	5.89 – 8.31	9.70	4.60 – 10.01	4.54 – 10.49	0 – 9.60	0 – 12.56	3.93 – 11.81	3.19 – 9.10	3.39 – 8.60	6.52 – 11.05	8.29 – 8.47	8.66
Average grape 5 yield in t/ha	7.10	9.70	7.10	7.75	6.85	7.06	7.35	7.24	6.33	8.03	8.38	8.66
Corresponding temperature value	19.75 – 20.22	20.22 – 20.69	20.69 – 21.16	21.16 – 21.62	21.62 – 22.09	22.09 – 22.56	22.56 – 23.03	23.03 – 23.50	23.50 – 23.96	23.96 – 24.43	24.43 – 24.90	24.90 – 25.37