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Climate Fluctuations and Growing Sensitivity of Grape Production in Abruzzo (Central Italy) over the Past Sixty Years

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Abstract: The sensitivity of the agricultural production system to short- and long-term climate variations significantly affects the availability and prices of food resources, raising relevant issues of sustainability and food security. Globally, productive systems have adapted to climate change, leading to increased yields over the past century. However, the extent to which these adaptations mitigate the impacts of short-term climate fluctuations, both extreme and ordinary, remains poorly studied. To evaluate the vulnerability of crop yield to short-term climate fluctuations and to determine whether it changes over time, we conducted a statistical analysis focusing on one of the main crops in the Abruzzo region (central Italy) as a case study: grape. The study involves correlation analysis between opportune climatic indices (SPI and SPEI) and grape yield data over the sixty-year period from 1952 to 2014, aimed at evaluating the impact of short-term climatic fluctuations—both extreme and ordinary—on crop yield. Our findings reveal an increasing correlation, mainly in the summer–autumn season, which suggests a rising sensitivity of the productive system over time. The observed increase is indicative of the Abruzzo grape production system's adaptation to climate change, resulting in higher overall yields but not enhancing the response to short-term climatic fluctuations.

Keywords: climate variations; grape yield; climatic trend; correlation analysis; climate adaptation; sustainability

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1. Introduction

Short- and long-term climate variations raise important sustainability issues, due to their potential economic and social impacts. These impacts are related to fluctuations in agricultural yields and volatility in prices and production costs of essential food resources, affecting their availability to the population [1–4]. In this context, studying local climate is crucial for effective management of the agricultural production sector.

The Mediterranean region, including Italy, is particularly vulnerable to current and future climate changes due to its transitional position between warm and temperate climates and its complex orography [5–8]. In central Italy, several studies have identified climate trends associated with significant increases in average and extreme temperatures [9–12]. Among the various indices used to describe climatic conditions [13–16], the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) are among the most frequently utilized [17]. Recent studies have analyzed the correlations of these indices with anomalies in crop yields in different regions of the world [18–24].

While numerous studies have examined the long-term interactions between climate variations and crop production, including the role of carbon emissions from land use [25] and climate adaptation strategies [26–30], the impacts of short-term climate fluctuations on agricultural systems, and their variation over time, have received less attention. While studies like Mazhar et al. [31] and Ostberg et al. [32] have explored this topic, the time-varying sensitivity of agricultural systems to climate change and its implications for price stability remain understudied. A few notable exceptions include Tran et al. [33], who investigated the effects of year-to-year climate variability on agricultural commodity prices in a competitive market, and Iizumi and Ramankutty [34], who examined the impact of climate change on crop yield variability. Similarly, Segerstrom [35] analyzed the volatility of coffee prices in relation to climate change. However, the literature on this topic remains limited. To address this gap, further research is needed to explore the temporal dynamics of short-term climate fluctuations on crop yields and develop standardized methods for monitoring the response of agricultural systems. Ultimately, these monitoring techniques could be extended to probabilistic forecasting of yields and market prices.

In the present study, we carried out a statistical analysis involving grape yield and climatic time series to identify changes in the sensitivity of the agricultural production system to climate variability over time. In studying the response of the crop production system to climate fluctuations, it is important to consider that the system is characterized by a complex interplay of ecosystem, technical, and engineering solutions, and economic variables (Figure 1). In the event of unfavorable climatic conditions, a series of technical solutions (e.g., irrigation, frost protection, etc.) may be implemented to mitigate the negative effects and optimize yield, albeit at a cost. However, these technologies may not always be sufficient to achieve desired crop yield targets, and their use depends on an economic viability assessment. The crop production system can be viewed as a dynamic system, including three sub-systems (Figure 1): (i) land ecosystem (LE), (ii) interventions (INT) and (iii) economic viability condition (EC). The input is a climatic variable, described by an opportune index, which provides the input I_1, and the output is the crop yield value. I_1 is the input for the sub-systems LE and INT. The EC sub-system produces a second input (I_2) for LE, which is intentionally anticorrelated with I_1, in order to minimize the effects of unfavorable climatic conditions and optimize the output.

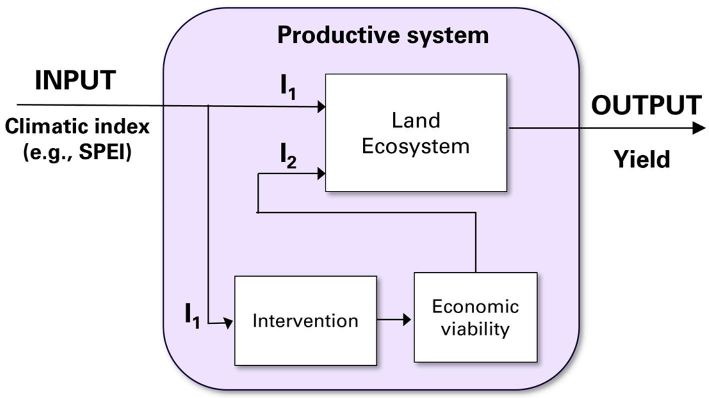

Figure 1. The agricultural productive system viewed as a simple dynamic system, constituted by three main subsystems.

Therefore, our analysis studies the agricultural production system as it presents itself, i.e., inclusive of all ecosystem-related, technological, and financial variables. Here, we analyze only the input (climate indices) and output (agricultural yield) variables of this system. In other words, the production system is studied here according to a black-box model, i.e., in terms of input–output relationships, while the existence and interactions of other state variables are acknowledged, but these are not quantified.

The effects of climate change on agricultural systems are complex and highly variable, depending on factors such as region, farming system and specific crop. Moreover, the primary drivers of yield variability—whether they be mean values, variability, or extremes of temperature and precipitation—are often not known a priori (e.g., [3]). Additionally, impacts can be both direct and indirect, with the latter including effects such as pest outbreaks and disease propagation [3].

This study contributes to a broader research project that investigates the relationships between climate variables and agricultural yields at the provincial scale for key crops in the Abruzzo region (central Italy), including wheat, olive, and grape [23,24]. While Guerriero et al. [24] conducted a detailed regression analysis between climate indices and wheat yields, pointing out a sensitivity trend over time, this study focuses on grape production. Comparing these two crops is particularly interesting given their distinct market dynamics. Wheat, primarily used for basic food products, is traded on global markets. In contrast, grapes are often associated with high-quality local products (e.g., wine), with prices influenced by factors such as varietal characteristics and regional reputation. This study lays the groundwork for future research on the impact of climate variability on market prices. Given the unique characteristics of grape varieties in the study area, analyzing grape production could provide valuable insights into the relationship between climate and market prices.

To address these research questions about the impact of short-term climatic fluctuations on grape production, we conducted a correlation analysis between climate indices (SPI and SPEI on one, three, and six months, estimated for different months of the year) and grape yield deviations from expected values over the period 1952–2014. Our analysis aims to (i) identify trends in correlation with specific climate indices, which can be interpreted as changes in system sensitivity, (ii) determine the most influential climate indices over time, and so (iii) pinpoint the most sensitive phenological stages, and (iv) provide a comprehensive picture of the effectiveness of climate adaptation strategies in the Abruzzo grape production system.

2. Materials and Methods

2.1. The Study Area

The study area includes the four provinces of the Abruzzo region, which cover approximately 11,000 km^2 in central Italy (Figure 2). This region is characterized by a Mediterranean climate with a marked areal variability, due to its complex geomorphological settings.

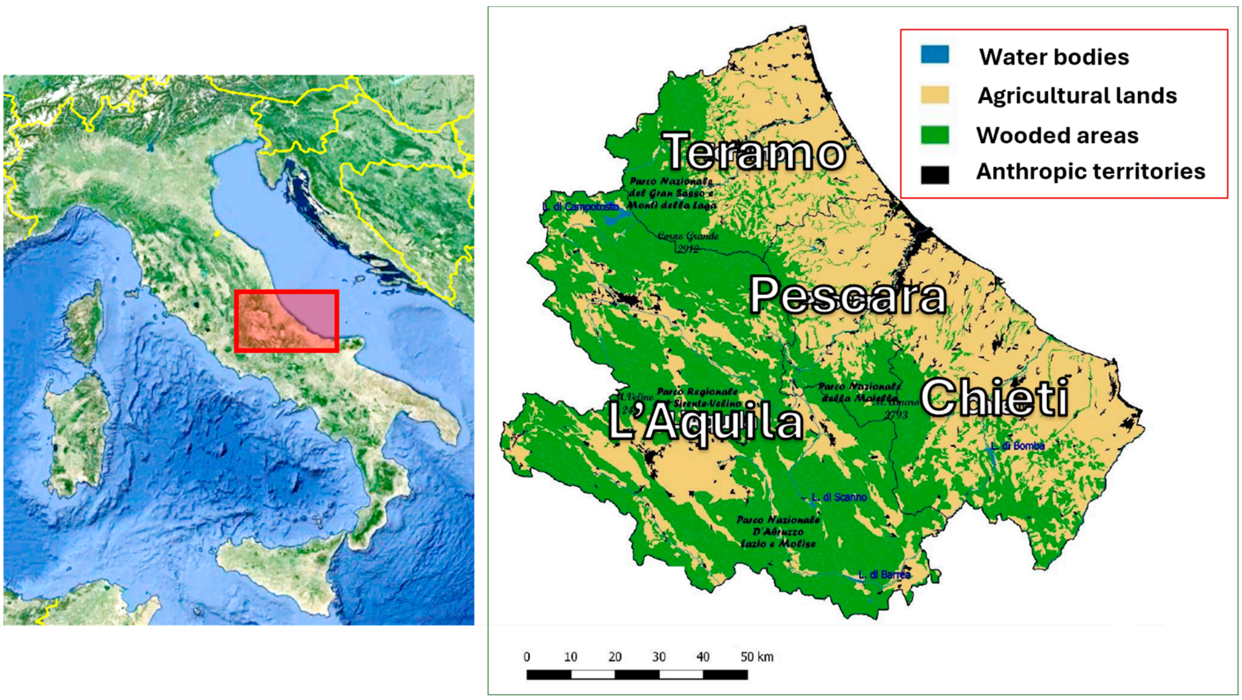

Figure 2. Location and land use of the study area. Modified from [23].

This structure is the result of tectonic activity that peaked in the Neogene and is still ongoing, accompanied by intense seismic activity and ground deformation [36,37], which has conferred an orography characterized by alternating mountain chains and valleys, oriented NW-SE [38]. Consequently, Abruzzo spans a wide range of altitudes, from coastal to high mountain environments, which can be distinguished in: (i) the internal mountainous belt, presenting complex orography (Figure 2) and characterized by various micro-climates, with a prevalent continental climate, with hot summers and cold winters, and (ii) the external hilly and coastal strip (Figure 2), characterized by a more uniform mediterranean climate, with hot summers and mild winters. The provinces of Chieti, Teramo and Pescara include both coastal and internal hilly and mountainous areas. The Province of L'Aquila is the most inland and exhibits a more complex geomorphological structure and a wider distribution of climates.The region studied has a well-developed agricultural sector, which has seen significant increases in crop yields and production over the past sixty years. Crop production is concentrated in the coastal areas and inland plains. Abruzzo exports agricultural products such as grape, olive, and wheat, as well as high-price processed products such as olive oil and wine. Grape production is primarily concentrated in the province of Chieti, which accounts for about three-quarters of the total regional production.

The statistical analysis of grape production can provide valuable information into the interaction between climate and the production system, providing insights for optimizing investments under unfavorable climatic conditions.

2.2. The Utilized Dataset

The climate analysis presented in this study is based on time series of daily and monthly thermo-pluviometric data, provided by the official publications of Regional Hydrographic Services [39,40], recorded in 37 stations appropriately selected and uniformly distributed across the regional territory, covering the period from 1952 to 2014.

Crop production data utilized are obtained from the Italian National Institute of Statistics (ISTAT) [41,42] and consist of annual time series for cultivated agricultural area and total production, for grape, over the same period as the climatic data.

2.3. Statistical Anaysis

Based on the climatic data, the following analyses were carried out: (i) climate classification using Péguy climographs, (ii) calculation of SPI and SPEI indices, over the studied time range (1952–2014), at one, three, and six months, for different months of the year, and (iii) correlation analysis between these indices and grape production in the Chieti province.

The Péguy classification was carried out over two thirty-year time ranges, 1952–1982 and 1983–2014, in consideration of different trend patterns in thermo-pluviometric and crop yield data [23].

Variations in crop yields over time depend on various factors beyond climate, such as new management practices, mechanization, etc., which have led to an overall yield increase in recent decades. To isolate variation due to climate, detrended and standardized values were calculated for yields (e.g., [19]). Detrending consists of considering, for each annual yield value, the difference (or residual) between detected value and that associated with a linear regression line (i.e., trend), defined in the thirty-year period (1952–1982 or 1983–2014) to which it belongs. From these residuals, the Standardized Yield Residual Series (SYRS) is obtained:

$$\text{SYRS} = (r - m)/s,$$

where r represents the residual, m is the mean of the residuals, and s is their standard deviation. Note that the use of the standardized variable does not imply the assumption of a particular probability distribution (e.g., Normal), but represents here only a convenient method of producing dimensionless data.

We then conducted several time series regression analyses for the Chieti province, comparing the grape SYRS with monthly, quarterly, and semi-annual SPI and SPEI indices, calculated over the months of the year going from March to December. The analysis was performed by calculating the Pearson coefficient between SYR and the considered SPI or SPEI in a certain month, on rolling 30-year windows, spanning the period from 1952 to 2014. By way of example, the first time window covered the time range 1952–1981, the second 1953–1982, and so on. This procedure provided a time series of correlation coefficients for each considered index and month of the year.

A linear regression model was selected for the correlation analysis between SYRS and SPI/SPEI. Although this model provides a less accurate description of the relationship between these variables compared to a parabolic model (e.g., [19]), it offers the advantage of providing additional insights into the effects of climate fluctuations. A positive correlation indicates that drought is a limiting factor for crop yield, while a negative correlation suggests that excessive moisture is the limiting factor. In other words, the absolute value of the Pearson coefficient indicates the weight of climatic fluctuation, with respect to all other causes, in affecting crop yield, whereas its sign indicates the way in which it impacts.

The several time series of correlation values achieved provide useful insights about the response of the productive system to climatic fluctuations, including ordinary and extreme events. To account for missing data (in the years 1984, 2001, 2004, 2005), we extended the window size when necessary, ensuring a sample size of 30. Statistical significance was assessed using Student's *t*-test at the 10% and 1% levels. For a sample size of 30, these significance levels correspond to absolute critical values of 0.30 and 0.46, respectively. A correlation coefficient exceeding 0.30 (in absolute value) indicates an unlikely spurious correlation, while a value greater than 0.46 suggests a highly significant relationship between the two series. The main steps of our analysis are summarized in Figure 3.

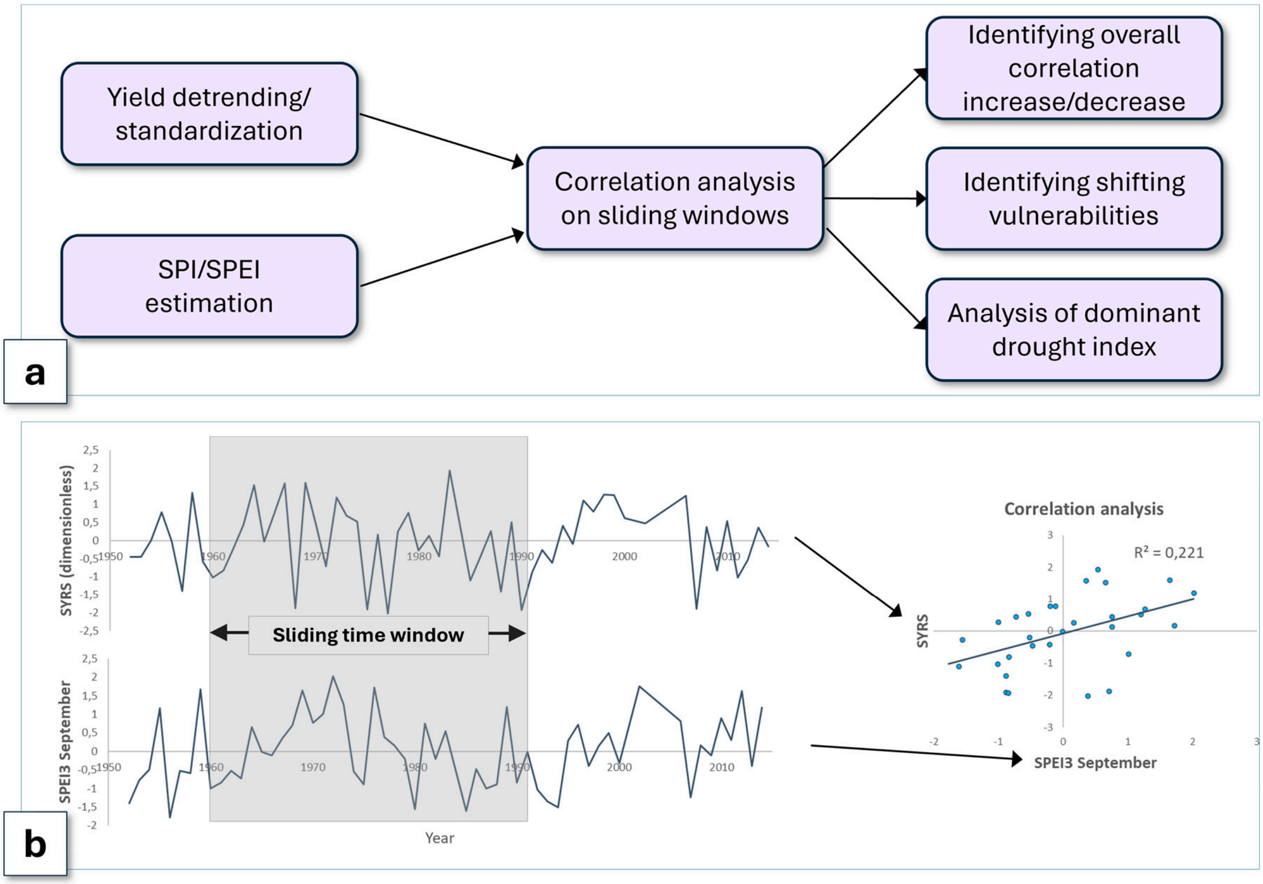

Figure 3. (**a**) Flowchart summarizing the analysis process. (**b**) Example of correlation analysis between SYRS and quarterly SPEI (SPEI3) of September, for grape in the Chieti province, over the time range 1960–1990.

3. Results

3.1. Grape Yield in the Chieti Province

This study analyzed total grape production in the province of Chieti, encompassing both table and wine grapes. Figure 4a illustrates the total grape production (tons/hectare) in the four provinces of Abruzzo, highlighting the concentration of the overall regional production in the province of Chieti. Additionally, the dashed line represents wine grape production in Chieti. Despite being fragmented and discontinuous, data points highlight a significant increase in the production of higher-quality wine grapes over the studied period from 1952 to 2014. This production picture indicates that the province of Chieti has invested more heavily in intensive grape production compared to the provinces of L'Aquila, Teramo, and Pescara, where such production is secondary to other crops such as wheat or olive. For these reasons, our statistical analysis focused on production in the province of Chieti, where the grape production system demands a high level of performance.

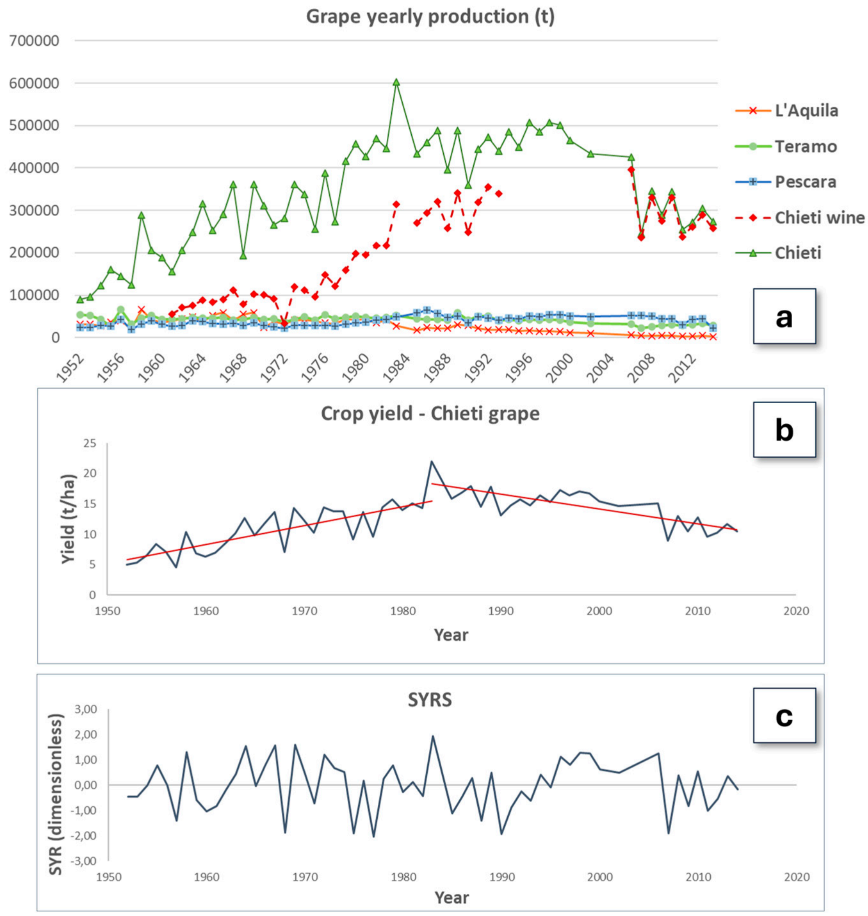

Figure 4. (**a**) Time series of total grape production (tons) in the four Abruzzo provinces. Red dashed line denotes the only wine grape produced in Chieti province. (**b**) Crop yield (t/h) of the Chieti province grape. (**c**) Time series of standardized yield residuals for grape yield.

Over the study period (1952–2014), grape yields in the Chieti province exhibited an overall increase according to a composite trend, which can be divided into two 30-year sub-periods: 1952–1982 and 1983–2014 (Figure 4b). Yields showed a significant upward trend in the first period and a slight downward trend in the second. Figure 4c, which illustrates the results of the detrending process (Section 2.3), indicates that the variability of grape yields did not change significantly over the entire study period (1952–2014). In other words, grape yield has exhibited enhancements in terms of overall increase but not in terms of reductions in year-to-year fluctuations.

3.2. Integrated Analysis of Climatic and Crop Yield Data

The climatic analysis revealed that daily maximum and minimum temperatures show a slow but statistically significant increasing trend (significance > 10%, according to the Mann–Kendall test [23]), in the second thirty-year period. Furthermore, the climate exhibits a systematic shift from temperate to temperate–arid. Figure 5 illustrates an example of maximum and minimum daily temperature (yearly average) trends and climate classification according to the Péguy criterion, with a related shift for the provinces of L'Aquila—in which the changes are more evident—and Chieti.

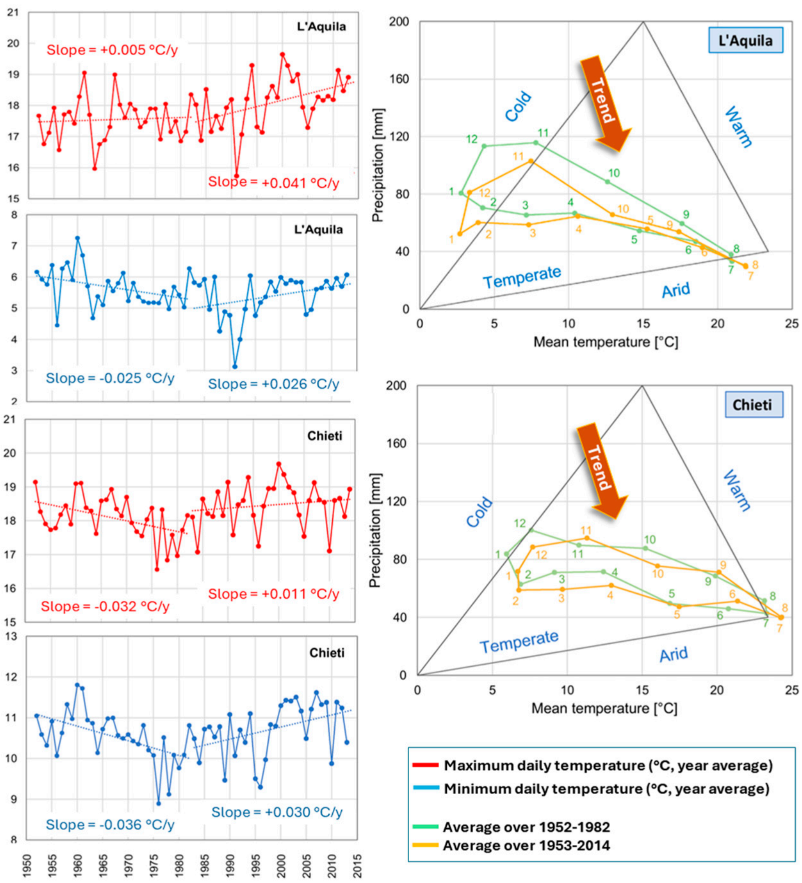

Figure 5. Time series of maximum and minimum daily temperatures and Péguy climate classification in the two considered time ranges, 1952–1982 and 1983–2014, for L'Aquila and Chieti provinces. Dotted lines denote trendlines over about thirty-year time ranges (from [23], modified).

The correlation analysis between fluctuations in crop yield and climate indices highlighted an overall increase in the Pearson coefficient (in absolute value) over time in the Chieti province. Figure 6 shows the results of the correlation analysis between grape yield and drought indices for such province. The symbols SPI1, SPI2, and SPI3 in Figure 6 denote the one-month, quarterly, and half-yearly SPIs, whilst the column number denotes the month in which the index is calculated. The same applies to the SPEIs. The correlation was calculated over five successive time windows, each approximately 30 years long. For each time window, we constructed a panel in which each cell represents a specific SPI/SPEI calculated for a particular month (March to December). Cell color indicates the level of significance. Light-colored cells (red or blue) denote a correlation with 10% significance (i.e., a likely existing correlation), whilst dark red or blue denotes 1% significance (i.e., strong correlation). It is recalled that positive or negative correlation does not inherently indicate a favorable or unfavorable climate impact, but whether drought or excessive humidity is a limiting factor for yield.

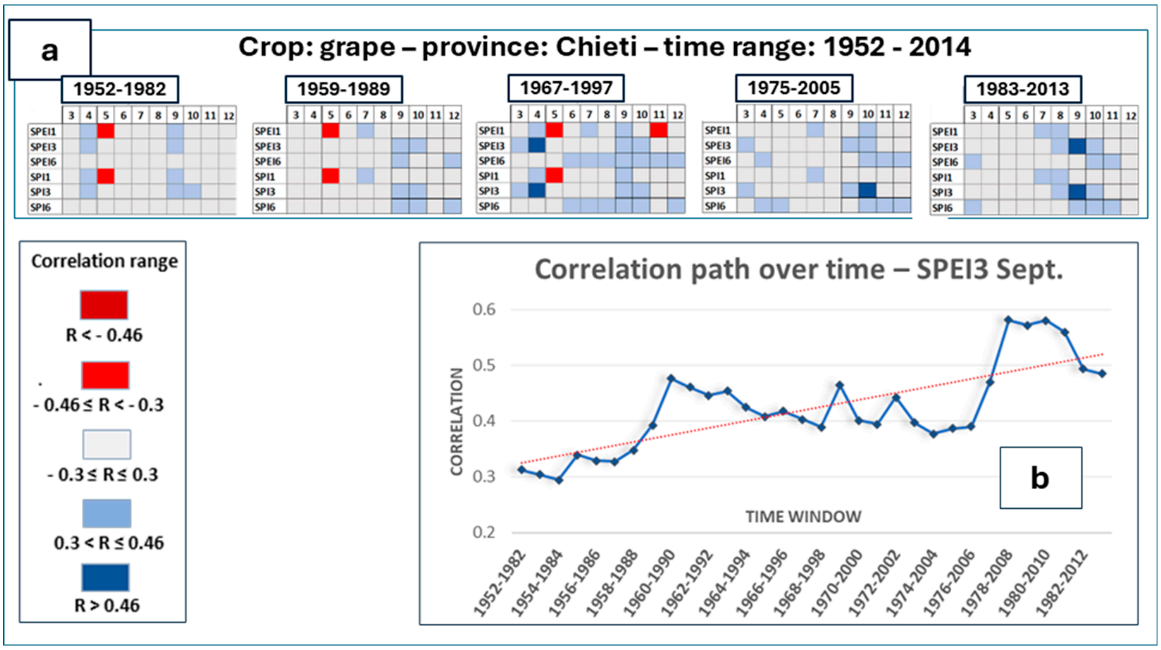

Figure 6. (**a**) Identified correlation coefficients between detrended crop yield (SYRS) and relevant SPI and SPEI indices for grape in the province of Chieti and for five sequential time windows. The correlation threshold (absolute) values of 0.3 and 0.46 are associated with a statistical significance of 10% and 1%, respectively. An increase in the number of colored cells, and mainly of dark red or blue ones, denotes a growing correlation between crop and climatic oscillations. (**b**) Correlation values between SYRS and SPEI3 of September, calculated in a time window of thirty years, sliding over the whole studied time range (1952–2014), with the trendline.

We remark here that the main aim of this study is the identification of systematic variations, over time, of the correlation between fluctuations in crop production and in drought indices. In the panels of Figure 6a, we observe an overall increase in the correlation (which is evidenced by an increase in the number of colored cells) between SPI/SPEIs and grape yield over time. Furthermore, a shift in colored cells is observed towards the August–October months, which allows us to identify the index showing the most pronounced rise in correlation, i.e., the quarterly SPEI (and SPI) of September, whose time series and trend are illustrated in Figure 6b.

4. Discussion

4.1. Interpretation of the Statistical Results

The achieved time series of correlation values corresponding to consecutive time windows (Section 2.3) provide key information about the relationship between climatic oscillations and crop yield fluctuations, within a framework of climate shifting towards a more warm–arid condition.

i. This reveals a changing sensitivity to climate fluctuations. The observed overall increase in the correlation coefficients in absolute value over time can be interpreted as a greater vulnerability of the grape production system to climatic fluctuations.
ii. This points out shifting vulnerabilities over the month of the year. The migration of the highest correlation values from the spring season towards the autumn one can shed light on the specific phenological stages that become increasingly important in terms of the climate-vulnerability of yields.
iii. The trends of the various observed correlation coefficients point out that the quarterly SPIs and SPEIs of September are becoming the most impactful drought indices, as these show the most pronounced and consistent trend over time. The trend analysis of

the dominant index provides a useful tool for monitoring and potentially predicting climate-induced short-term yield variations [24].

Comparing our findings for grape yields to those of wheat in the Abruzzo region [24] reveals striking similarities. Both crop systems have experienced increased yields over time, particularly notable and persistent for wheat. However, this trend has not been accompanied by a reduction in year-to-year fluctuations. These fluctuations are of particular interest as they highlight the system's inability to maintain high performance under unfavorable climatic conditions. Fluctuations in crop yields, even positive ones, can disturb the complex market equilibria involving producers, distributors, investors, and consumers. By way of example, uncontrolled price volatility can lead to temporary increases that burden consumers or temporary decreases that harm producers, distributors, or other stakeholders such as investors, insurance companies, etc.

The analysis presented in this study complements previous research on grape production [43,44] and that of other crops [24,45] in central Italy and other parts of Europe [18], providing additional insights into how agricultural yields respond to short-term climate fluctuations. By integrating these findings, we can develop a more comprehensive understanding of the impact of both short- and long-term climate variability on agricultural productivity.

Our statistical analysis suggests that climate adaptation strategies in the Abruzzo grape production system, similar to those observed for wheat, have improved overall annual production but have not mitigated the effects of short-term climate fluctuations.

4.2. Limitations of This Study and Perspectives for Future Research

A limitation of this study is the incomplete dataset, which extends only to 2014. This limitation is due to challenges in obtaining complete meteorological (for all 37 monitoring stations) and agricultural production data. To ensure a dataset with minimal interruptions, we analyzed the period from 1952 to 2014. Additionally, due to data availability constraints for grape yield, we considered total grape production, encompassing both table and wine grapes, despite their different yields and varying cultivated areas over time in Abruzzo. While detrending helped to mitigate the effects of these variations, the use of a more comprehensive dataset covering a longer period, including separate data for table and wine grapes, would be beneficial for a more in-depth analysis in future research.

Additionally, our analysis was focused on the province of Chieti, as a previous study [23] indicated that the other provinces in Abruzzo, where grape cultivation is a secondary production, exhibited lower correlations between grape yield and climate indices. While this allowed for a more in-depth analysis, it limits our understanding of spatial variability in the region.

This study, besides providing insights into the evolution of relationships between climate and grape yield, could furnish a useful basis for developing probabilistic forecasting models, as illustrated by Guerriero et al. [24]. Nevertheless, such an endeavor would require careful consideration of model selection and validation, which will be a subject for future research. Finally, integrating our results with models of price variation, similar to those employed by Tran et al. [33], or also [28,35], would provide a more comprehensive understanding of the economic implications of climate variability on the grape sector.

5. Conclusions

In this study, we conducted a statistical analysis involving climatic data and indices (SPI and SPEI), and grape yields, on a provincial scale in the Abruzzo Region, covering the time range from 1952 to 2014.

Over the investigated sixty years, the climate in the region shifted towards more warm–arid conditions. An overall increasing correlation between grape yields and drought indices has been observed, which can be interpreted as a signal of increasing yield vulnerability to year-to-year climatic fluctuations, within a framework of changing climate.

The period of the year, and corresponding phenological phase, when grape yield in the Chieti province is becoming more sensitive to climate fluctuations is between August and

October, with the September quarterly SPI and SPEI indices exhibiting the most pronounced upward trend for the correlation coefficient. Contrarily, in the spring season, correlation values exhibited a decrease over time.

The statistical approach here illustrated furnishes a comprehensive picture of the evolving climate–yield relationship for the studied province, so providing a robust framework for monitoring climate impacts on crop yields and for rational agricultural sector management and planning. The observed correlation increase is indicative of the grape production system's adaptation to climate change, resulting in enhanced overall yields but not offsetting the effects of short-term climate fluctuations.

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Data Availability Statement: Name of the code/library: Data_Set_Grape_SYR_SPI-SPEI_.xlsx. Contact: vincenzo.guerriero@univaq.it; vincenzo.guerriero@unina.it. Software required: MS Office or equivalent. Program size: 186 KB The data are available for downloading at the following link: https://github.com/vincenzo-guerriero/Grape_Abruzzo_SYR_SPI_SPEI_Time_Series (accessed on 15 November 2024). Temperature and precipitation data have been published in the Annals of the Italian National Hydrographic and Mareographic Service and are available, upon request, in digital form from the corresponding regional offices. Agricultural data from more recent years have been published by ISTAT in the Annals of Agricultural Statistics and are available in digital form in the ISTAT database http://dati.istat.it, accessed on 15 August 2023.

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