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Research article

Phenological relationships between meteorological extremes and agricultural yield

Barış DURMUŞ[1,*], **İhsan BULUT**[2]
[1]Department of Geography, Faculty of Sciences and Literature, Nevşehir Haci Bektaş Veli University, 50300, Nevşehir, Türkiye
[2]Department of Geography, Faculty of Sciences and Literature, Akdeniz University, Antalya, Türkiye
*Corresponding author email: barisdurmusdr@gmail.com

Abstract: Increasing temperatures with climate change and extreme events such as heat and cold waves, severe droughts, floods, storms, and hail significantly impact agricultural yield and food security. The Mediterranean Basin is particularly vulnerable in this regard. This study investigates the relationships between extreme temperature and precipitation values and agricultural yield rather than average climate parameters. Considering regional representativeness, production, and economic value, the annual wheat and barley yields of Burdur and Isparta provinces were compared with local meteorological data. Similarly, orange yields from Antalya's Finike station and olive yields from the Antalya Airport station were analyzed. Fourteen extreme temperature and precipitation indices were identified and analyzed using the ClimPACT2 software package. To eliminate linear trends in yield data caused by technological advancements, a standardization method was applied. Relationships between datasets were evaluated using Pearson's correlation coefficient. The study found significant correlation coefficients between temperature and precipitation extremes and annual cereal yield, ranging from -0.48 to 0.38, explaining 10-23% of yield variance. For annual orange yield, coefficients ranged from -0.76 to 0.87, explaining 57-75% of yield variance, while for annual olive yield, coefficients ranged from -0.63 to 0.70, explaining 39-49% of variance. A strong relationship was observed between yield values and drought or minimum temperature extremes. Significant relationships were identified during cereals' seed development and heading phases (winter-spring) and fruits' flowering and development stages (spring-summer). Under changing climatic conditions, agricultural yield and product quality are expected to be increasingly affected by extreme weather events, whose frequency and severity are escalating.

Keywords: Extreme Weather Events, Drought, Agricultural Yield, Phenology

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Introduction

The increasing frequency of extreme temperature and precipitation events due to climate change exerts significant pressure on agricultural ecosystems. Rapidly changing parameters such as temperature, precipitation, evaporation, and soil moisture cause sudden fluctuations in agricultural production (Aydinalp & Cresser, 2008; Hayaloğlu, 2019; Akalın, 2014; IPCC, 2019; Zaimoğlu, 2019; Türkeş, 2020). According to Intergovernmental Panel on Climate Change reports (IPCC, 2012; 2019), climate change is expected to intensify, affecting food security; increasing temperatures, droughts, floods, and other extreme events will directly impact agricultural yield. The Mediterranean Basin has a higher agricultural risk profile concerning climate change (Giannakopoulos et al., 2009; Giorgi & Lionello, 2008; Iglesias et al., 2011). According to the MedECC (2020) report, climate change in the Mediterranean Basin is expected to lead to more extreme weather events, economic losses, soil erosion, water scarcity, land degradation, agricultural and hydrological drought, and variability in agricultural yields. Furthermore, extreme weather events may also have global impacts, such as reduced agricultural exports and rising food prices, in addition to regional effects.

Extreme weather events occurring during the phenological stages of plants can directly affect the plant development process, leading to changes in the quantity or size of agricultural products at harvest. Although studies in the literature generally focus on the relationship between agriculture and climate using average climate parameters, recent research has increasingly examined the phenological relationships between extreme weather events and agricultural yield. Changes in crop patterns and plant development due to climate change (Paria et al., 2022); variability in yields (Troy et al., 2015; Vogel et al., 2019); spatial changes in agricultural lands, increases in diseases and pests (Butterworth et al., 2010; Skendžić et al., 2021); chemical and biological degradation in water resources and soil (IPCC, 2019); increases in soil and wind erosion and environmental pollution (Eekhout and de Vente, 2022); and various extreme events (Gornall et al., 2010) are occurring as a result.

Changes in meteorological processes also change crop patterns and phenological stages. Öztürk et al. (2017) reported that wheat yield planted in winter decreased due to early spring onset in Denmark; Hakala et al. (2012) found that summer droughts and increased extreme precipitation during the planting season reduced barley yields in Finland. Conversely, Harkness et al. (2020) suggested that warmer summers in the UK might increase wheat yields but also bring new risks associated with extreme precipitation. Uleberg et al. (2014) noted that rising temperatures also increase agricultural diseases. While changing climatic conditions can create favorable agricultural opportunities in cold regions and northern latitudes, extreme variability in weather conditions brings new dangers.

In their global study, Vogel et al. (2019) reported that, depending on the crop type, the impact of extreme climatic conditions on agricultural yields ranges from 18 to 43 %, and that efficient irrigation activities reduce the effects of extreme temperatures. A study on crop yields in the United States (Troy et al., 2015) also reported that irrigation relatively reduces the effects of all extreme temperature conditions. Zhu and Troy (2018) reported that extreme temperatures during the growing season of agricultural crops (maize, wheat, soya beans) cause yield reductions. Uzun and Ustaoğlu (2022), in their study on the agricultural effects of variability in climatic conditions in the Mediterranean Region, stated that olive yields decreased during dry periods in 1991, 1997, 2009, 2015 and 2016 strong El Nino years.

Wheat, which is a cool and temperate climate plant resistant to cold weather conditions, requires temperatures between 1-5°C during the sowing period, around 8-10°C during the sprouting phase and above 19°C during the spike period and grows in regions where annual rainfall is between 350-1150 mm (Bulut, 2006). Barley, which is another cool-climate cereal similar to wheat in terms of growing conditions, can be grown in regions with high relative humidity and its cultivation is largely dependent on rainfall (Keskin, 2011). Temperature, wind, frost, dew, humidity and insolation periods are important factors that directly affect the yield and fruit quality of citrus trees. While the orange product can withstand up to -5°C, the length of cold days directly affects the yield and quality of the product. The growing phase of orange starts at 12°C, and the fastest growth occurs at 25-31°C and stops at 37-39°C. The yield of orange, which needs humid environments, decreases in low humidity conditions (Kaygısız & Aybak, 2000). Olive trees, characteristic of the Mediterranean climate, are resilient between -7°C and 40°C. The climatic requirements of olives are as follows; they need cooling (below 7°C) during the flowering period, 15-20°C during the flowering phase, 20-25°C during the fruit formation and growth phase, 15°C during the maturity phase and 5°C until the harvest period. Heatwaves during pollination and fruit setting hinder production, while cold snaps damage flowers, branches, and fruits. Additionally, periodicity in olive trees, influenced by physiological structure and agricultural practices, leads to yield fluctuations (Ergün et al., 2009). While agricultural product yield can be controlled with irrigation activities in case of lack of rainfall, yield may decrease in periods of extreme rainfall.

Methods

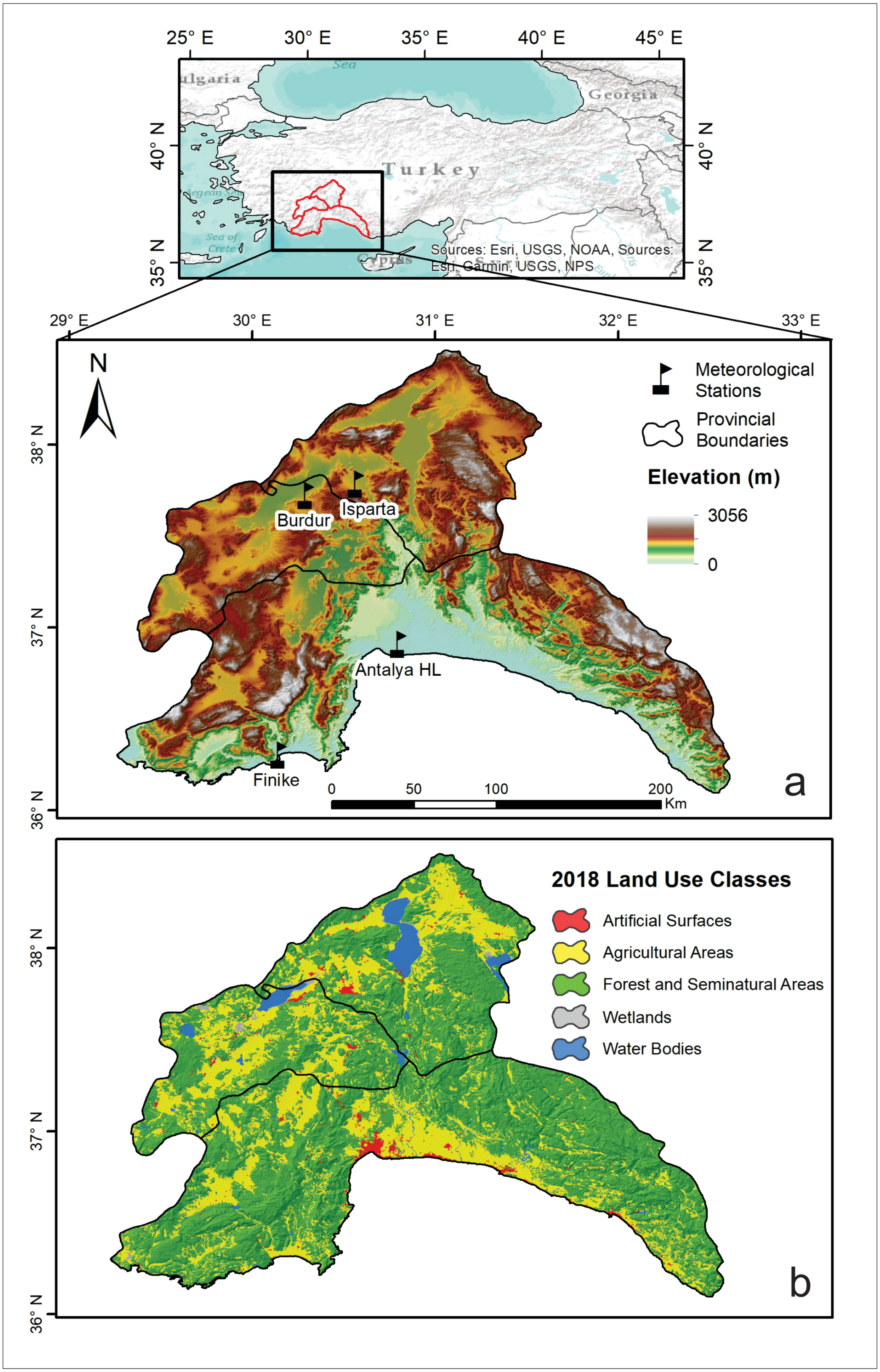
Study Area

The study area includes the provinces of Antalya, Burdur, and Isparta in the Mediterranean Region of Türkiye (Figurea). The coastal plains of Kumluca, Finike, and Antalya, as well as the inland plains of Gölhisar, Korkuteli, Elmalı, Tefenni, Isparta, and Burdur, form the region's main agricultural lands. Various fruits, vegetables, and cereal crops are grown throughout the region. Citrus and olive production dominate in Antalya's coastal areas, while wheat and barley are the most cultivated crops in the provinces of Burdur and Isparta. In 2018, agricultural land use was observed to be fragmented due to complex topographical conditions (Figureb). Agricultural activities are carried out on alluvial plains along the coast and tectonic and karstic (uvala, poljes) plains inland, as well as around water structures. The region's climate varies with altitude: the coastal areas experience a typical Mediterranean climate, higher altitudes experience a cool and relatively rainy Mediterranean mountain climate in summer and snowy winters, while the interior regions experience dry summers and cold winters under a continental climate (Atalay & Mortan, 2011). Depending on the topographic formations of the region, climate characteristics also change over short distances.

Data

To analyze the relationships between extreme weather events and crop yields phenologically, daily temperature and precipitation data from the Antalya Airport, Finike, Burdur, and Isparta meteorological stations for 1980–2019 were obtained from the Turkish Meteorological Service. The cultivated and harvested area (decare), production (tons) and yield (kg/decare) values for wheat and barley products were obtained from Burdur and Isparta provinces between 1980-2019. For the same period, data on orange and olive production, including orchard areas (decares), number of fruit-bearing trees, production (tons), and yield (kg/tree), were obtained from the Turkish Statistical Institute (TUIK). Since the data obtained from TUIK started in 1991, the missing data until 1980 were obtained from the annual agricultural production reports in the library archive of the Turkish Statistical Institute (TUIK Library, 2020).

According to wheat production data for Burdur province, 148,974 tons of production is achieved on a cultivated area of 696,129 decares. The average yield is 217 kg/da, and the linear trend value of the yield is $R^2=0.29$ (Figure 2. a). According to barley production data, 71,445 tons of production is carried out on a cultivated area of 279,754 decares. The average yield is 256 kg/da, and the linear trend value of the yield is $R^2=0.26$ (Figure 2. b). According to wheat production data for Isparta province, 98,797 tons of production is achieved on a cultivated area of 482,837 decares. The average yield is 206 kg/da, and the linear trend value of the yield is $R^2=0.07$ (Figure 2. c). According to barley production data, 86,245 tons of production is carried out on a cultivated area of 352,992 decares. The average yield is 244 kg/da, and the linear trend value of the yield is $R^2=0.03$ (Figure 2. d).



Sources: Esri, USGS, NOAA, Sources: Esri, Garmin, USGS, NPS

Figure 1. (a) Digital Elevation Model (DEM) of the study area and (b) land use classes (CORINE, 2018)

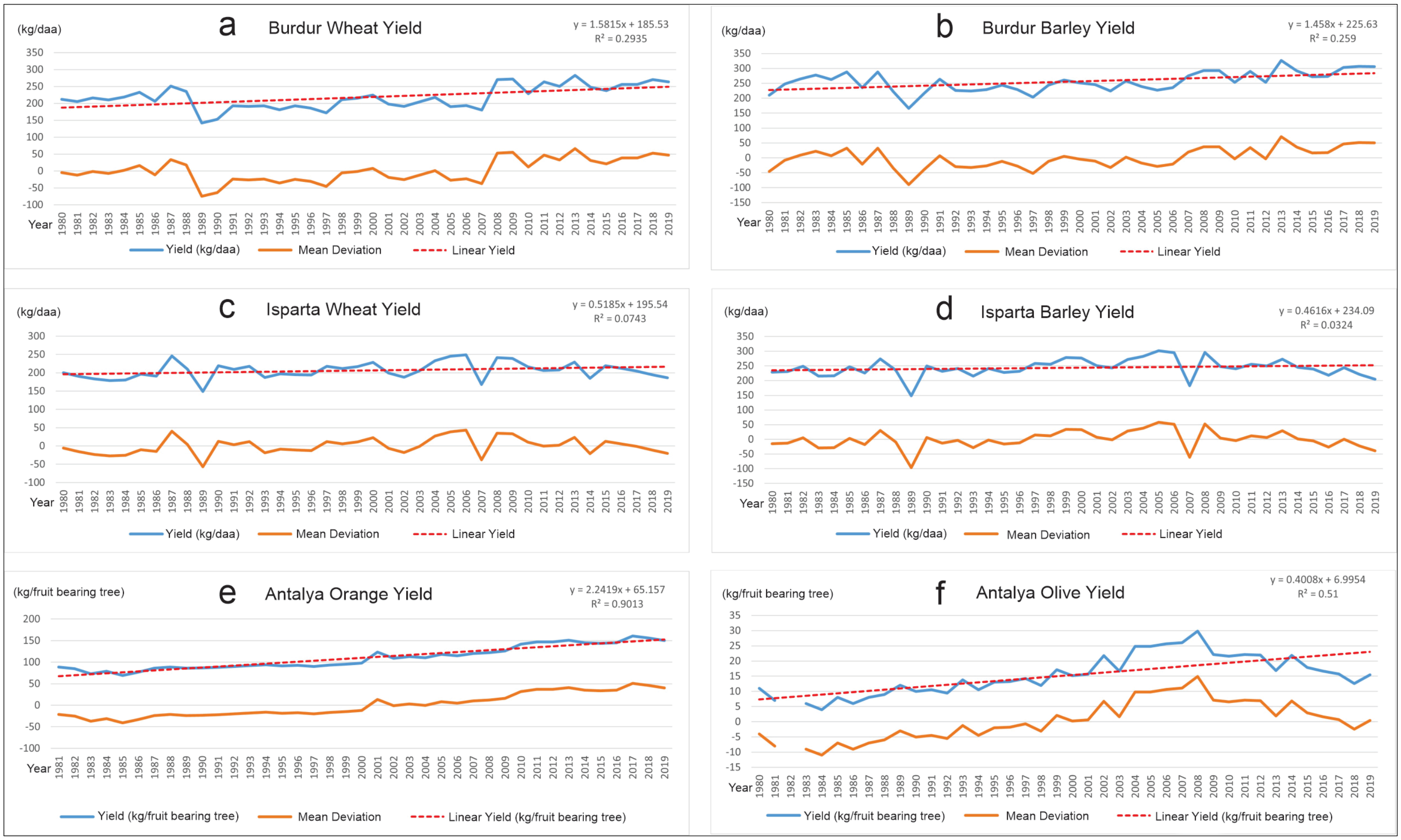


Figure 2. Time series and statistics of agricultural crop yields in the study area

Considering Finike's significance as a major and intensive production area for oranges, as well as its regional representativeness and the economic value of the product, temperature and precipitation data from the Finike meteorological station were used. For olive production, data from the Antalya Airport meteorological station were utilized. According to orange production data for Antalya province from 1981 to 2019, an average of 331,335 tons of production is achieved from a total orchard area of 120,207 decares. The average yield is 110 kg per fruit-bearing tree, with a linear trend value of R^2=0.9 (Figure 2. e). According to average olive production data for Antalya province from 1980 to 2019, an average of 46,851 tons of production is carried out from a total orchard area of 126,850 decares. The average olive yield is 15 kg per fruit-bearing tree, with a linear trend value of R^2=0.51 (Figure 2. f).

Methodology

The methodological flowchart of the study is presented in Figure 3. . After the data were obtained, various analyses were conducted to create datasets. Subsequently, meteorological data were organized according to phenological periods, and correlation analyses were performed.

Extreme index analyses were carried out on the 1980–2019 time series from the Antalya Airport, Finike, Burdur, and Isparta stations using the ClimPACT2 package within the R Studio statistical software (Alexander et al., 2006), and datasets were created. Additionally, trends in the time series of extreme indices, indicating increases or decreases, were determined using Mann-Kendall (Mann, 1945; Kendall, 1975) and Sen's Slope (Sen, 1968) analyses. Extreme indices associated with agricultural yield values have been determined for the study area based on literature studies (Troy et al., 2015; Vogel et al., 2019; Harkness et al., 2020). Data for 14 extreme temperature and precipitation indices derived from daily temperature and precipitation records between 1980 and 2019 were used (Table 1). The CSDI, WSDI, and GSL indices were evaluated annually, while other indices were assessed monthly. Before proceeding with correlation analyses, the extreme index values were reorganized to align with the phenological periods/months of the respective crops.

Crop production values generally exhibit an upward trend as a result of continuously evolving and improving scientific and technological practices in agricultural activities. Moreover, crop production volumes must also increase to meet the needs of growing populations and support national economies. To eliminate the environmental and technological effects driving this linear increase in production, standardization methods are frequently applied to time series. The time series obtained through the standardization of crop production values are used in correlation and regression models.

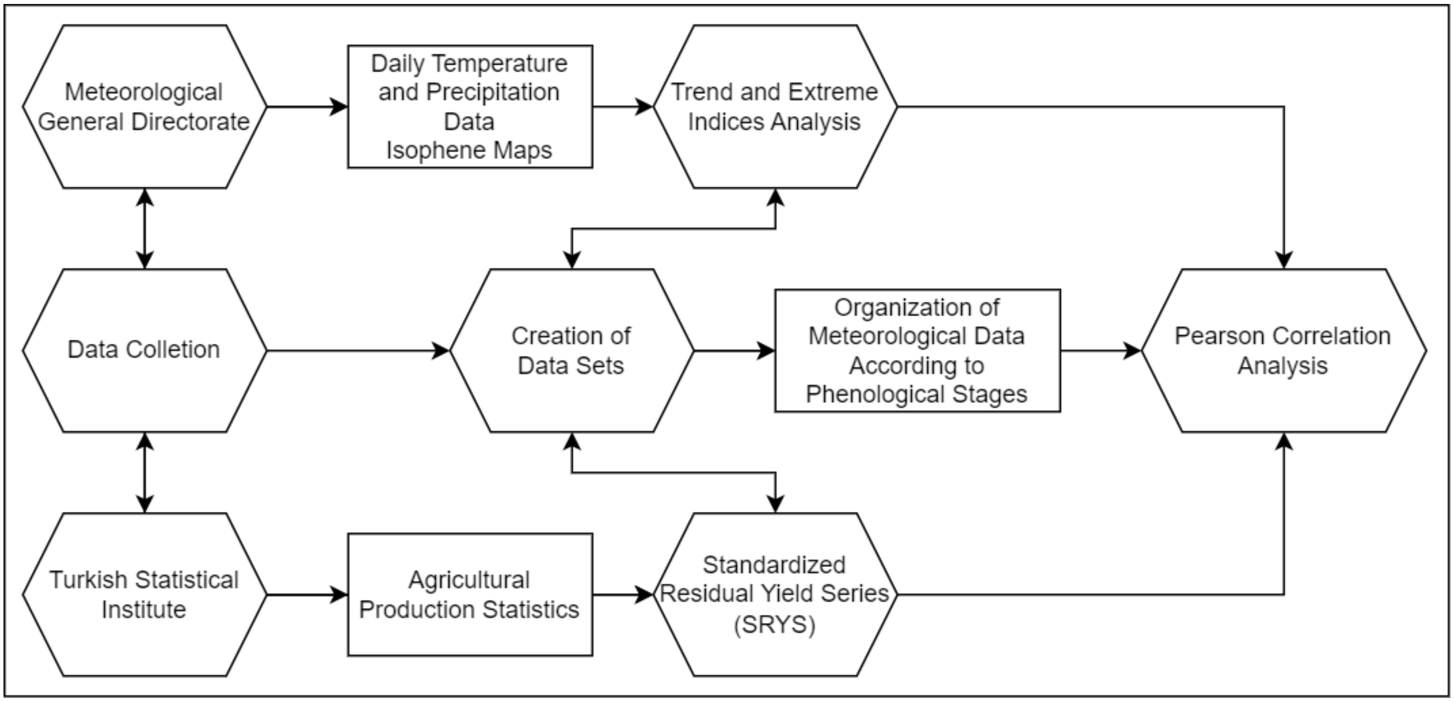


Figure 3. Research flowchart

Table 1. Indices of extreme weather events used in the study and associated with agricultural crop yields

Indices	Definition	Scale
TXm - Average Maximum Temperature	Daily average maximum temperature	Monthly
TXx - Absolute Maximum Temperature	Daily maximum temperature	Monthly
TNm - Average Minimum Temperature	Daily average minimum temperature	Monthly
TNn - Absolute Minimum Temperature	Minimum temperature minimum	Monthly
TN10p - Cool Nights	Days when Tmin is below the 10th percentile of the normal	Monthly
TX90p - Hot Days	Days when Tmax exceeds the 90th percentile of the normal	Monthly
DTR - Daily Temperature Range	Tmax – Tmin	Monthly
FD - Frost Days	Days when the minimum temperature is < 0°C	Monthly
SPEI - 6	6-month standardized precipitation evapotranspiration index	Monthly
PRCPTOT - Annual Total Precipitation	Total precipitation ≥ 1 mm	Monthly
Rx5day - 5-day Maximum Precipitation	Maximum precipitation amount over 5 consecutive days	Monthly
GSL - Growing Season Length	Total days between the first 6 days when $T > 5$°C and the first 6 days when $T < 5$°C	Annual
CSDI - Cold Spell Duration Index	Number of consecutive days with Tmin < the 10th percentile of the normal	Annual
WSDI - Warm Spell Duration Index	Number of consecutive days with Tmax > the 90th percentile of the normal	Annual

The Standardized Residual Yield Series (SRYS) is calculated using the following equation (Potopová et al., 2016, p. 2068; XianFeng et al., 2018, p. 7; Hamal et al., 2020, p. 5; Waseem et al., 2022, p. 5):

$$SAVS = \frac{y_i - \mu}{\sigma}$$

here, y_i represents the residuals of yield values detrended from the linear trend; μ denotes the mean of the yield residuals, and σ represents the standard deviation. On the other hand, since extreme index data include sub-data types such as days, degrees, percentages, and precipitation, these values have also been subjected to the standardization process.

To determine the phenological periods of the agricultural products used in the study on a monthly basis, the isophene maps from the 2014 Türkiye Phenology Atlas prepared by the Turkish State Meteorological Service (MGM) (Şimşek et al., 2014) were utilized. The phenological periods of wheat and barley (sowing, germination, heading, and harvesting) are provided in Table 2. The phenological periods of orange (flowering, fruit setting, fruit development, ripening, and harvesting) are presented Table 3, while the phenological periods of olives are detailed in Table 4. The phenological periods of the crops in regions with differing climatic conditions approximately occur within the months indicated in the tables (Şimşek et al., 2014).

Table 2. Phenological stages of wheat and barley

Crops	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Wheat	Sowing			Seed Development Stage				Heading		Harvest	
Barley	Sowing			Seed Development Stage				Heading		Harvest	

Table 3. Phenological stages of orange

Fruit Crop	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Orange	Flowering	Fruit Set	Growth Stage					Harvest

Table 4. Phenological stages of olive

Fruit Crop	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Olive	Flowering		Fruit Set and Growth					Ripening and Harvest	

The relationship between the values of meteorological extreme indices and the yield values of the crops was calculated using the Pearson Correlation Coefficient method (Wright, 1921):

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{\left[n\sum x^2 - (\sum x)^2\right]\left[n\sum y^2 - (\sum y)^2\right]}}$$

for this study, the Pearson correlation coefficient (r) represents the relationship between the yield values (x) and the extreme index values (y), with n being the number of value pairs. A correlation coefficient close to 1 indicates a positive relationship, while the value close to -1 indicates a negative relationship. A coefficient of 0 suggests no relationship between the variables. Correlation values approaching 0 indicate a weak relationship, values between 0.4/0.6 and -0.4/-0.6 suggest a moderate relationship, and values close to 1 or -1 indicate a strong relationship. The statistical significance of the correlation coefficients was evaluated using a significance level of $p \leq 0,05$. Additionally, the percentage of variance in one variable that can be explained by the other variable is determined using the coefficient of determination (r^2) (Schober et al., 2018, p. 1765).

Results and Discussion

The relationships between standardized extreme weather indices and crop yields were examined phenologically. Correlation coefficients are presented in tables, where bold and colored cells indicate statistically significant results. Since correlation results do not imply causality, the levels of relationships were analyzed and interpreted within the study methodology.

Correlation Analysis Results Between Extreme Indices with Wheat and Barley Yields

The correlation relationships between the annual wheat yields in Burdur province and the extreme index values obtained from the Burdur meteorological station are presented in Table 5.

Statistically significant weak-to-moderate correlation relationships, ranging from -0.43 to 0.31, were identified. According to the coefficient of determination (r^2), extreme index values explain between 10% and 18% of the variance in the annual wheat yield.

Table 5. Correlation coefficients between extreme indices and annual wheat yield in Burdur province

Phenological Stages	Indices Months	txm	txx	tnm	tnn	tn10p	tx90p	dtr	fd	spei6	prcptot	rx5day
Sowing	**Oct**	0.19	0.09	-0.01	0.04	0.00	-0.02	0.24	0.05	-0.26	-0.17	-0.10
	Nov	**0.32**	0.08	0.12	0.28	-0.19	0.17	0.30	-0.16	**-0.34**	-0.06	-0.12
Seed Development Stage	**Dec**	0.29	**0.36**	0.06	0.14	-0.24	0.22	0.24	0.00	**-0.41**	-0.18	-0.14
	Jan	0.17	0.16	0.28	-0.02	-0.19	0.24	-0.25	-0.31	-0.27	0.19	0.14
	Feb	0.29	0.20	**0.38**	0.27	-0.24	0.31	-0.03	**-0.41**	-0.21	0.14	0.07
	Mar	0.08	0.19	0.18	0.02	-0.01	0.04	-0.08	-0.16	-0.15	0.00	-0.07
	Apr	0.22	0.21	0.21	0.24	-0.31	0.10	0.17	-0.24	-0.06	0.03	0.14
Heading	**May**	0.16	0.00	0.19	**0.31**	-0.17	-0.07	0.06	-0.31	0.03	0.19	0.14
	Jun	**0.33**	0.22	0.31	**0.38**	**-0.43**	0.25	0.25	-	0.11	0.17	0.06
Harvest	**Jul**	0.30	**0.34**	0.24	0.23	-0.19	0.20	0.27	-	-0.05	-0.14	-0.15
	Aug	**0.31**	**0.33**	0.23	-0.03	-0.14	0.27	**0.32**	-	-0.11	-0.04	-0.04
Annual Indices	**gsl:** 0.17		**csdi**: -0.30		**wsdi: 0.30**							

From the extreme indices showing a significant upward trend in terms of climatic statistics, the following values exhibited a positive correlation with annual wheat yield data: average maximum temperature (txm) for November, June, and August; absolute maximum temperature (txx) for December, July, and August; average minimum temperature (tnm) for February; absolute minimum temperature (tnn) for June and May; warm spell duration (wsdi) for October; and daily temperature range (dtr) for August. On the other hand, extreme indices showing a significant downward trend in terms of climatic statistics, such as cool nights (tn10p) for June, frost days (fd) for February, and the SPEI-6 drought index for November and December, exhibited a negative correlation with annual wheat yield data.

During the wheat sowing stage (November) and the early stages of seed development (December), weak to moderate positive correlations were identified between maximum temperature values and yield levels. On the other hand, negative relationships were observed between yield levels and increased drought conditions, which cause water scarcity and heat stress, particularly during winter months. Along with rising temperatures, the region also experienced a decline in the number of cool nights. In the heading stage (particularly in June), moderate negative correlations were detected between cool nights (tn10p) and yield. Higher nighttime temperatures during the heading stage increase respiration in plants, leading to greater energy consumption, reduced carbohydrate accumulation, and decreased grain filling, ultimately negatively affecting annual yield (Asseng et al., 2011). Increases in night temperatures explain 18% of the annual yield variances.

The correlation relationships between the annual barley yields in Burdur province and the extreme index values obtained from the Burdur meteorological station are presented in Table 6.

Statistically significant weak-to-moderate correlation relationships, ranging from -0.48 to 0.36, were identified. According to the coefficient of determination (r^2), extreme index values explain between 12% and 23% of the variance in the annual wheat yield.

Among the extreme indices showing a significant upward trend in terms of climatic statistics, the following exhibited a positive correlation with annual barley yield data: average minimum temperature (tnm) for January and February; absolute minimum temperature (tnn) for November and May; and growing season length (gsl) for October. Among the extreme indices showing a significant downward trend in terms of climatic statistics, the cool nights (tn10p) index for June and frost days (fd) for January and February exhibited a negative correlation with annual barley yield data.

Table 6. Correlation coefficients between extreme indices and annual barley yield in Burdur province

Phenological Stages	Indices Months	txm	txx	tnm	tnn	tn10p	tx90p	dtr	fd	spei6	prcptot	rx5day
Sowing	**Oct**	0.19	0.19	-0.06	-0.14	0.10	-0.02	0.29	0.15	0.11	0.28	0.57
	Nov	0.29	0.14	0.17	**0.34**	-0.29	0.10	0.22	-0.22	0.10	0.87	0.54
Seed Development Stage	**Dec**	0.25	0.21	0.01	0.15	-0.23	0.15	0.26	0.03	0.05	0.71	0.90
	Jan	0.24	0.19	**0.34**	0.12	-0.28	0.25	-0.25	**-0.34**	0.18	0.46	0.45
	Feb	0.25	0.23	**0.34**	0.23	-0.15	0.30	-0.04	**-0.44**	0.31	0.38	0.61
	Mar	0.18	0.21	0.27	0.13	-0.12	0.07	-0.02	-0.24	0.30	0.61	0.47
	Apr	0.10	0.19	0.05	0.18	-0.20	-0.06	0.12	-0.23	0.55	0.69	0.26
Heading	**May**	0.26	0.01	0.29	**0.36**	-0.20	0.04	0.12	-0.19	0.83	0.49	0.47
	Jun	0.31	0.30	0.30	**0.33**	**-0.48**	0.24	0.23	-	0.63	0.30	0.57
Harvest	**Jul**	0.17	0.27	0.07	0.09	-0.01	0.14	0.22	-	0.90	0.89	0.82
	Aug	0.28	0.30	0.21	-0.01	-0.09	0.23	0.28	-	0.64	0.91	0.97
Annual Indices	**gsl: 0.35**		**csdi**: -0.29		**wsdi**:0.19							

Positive correlations were found between the increase in minimum temperature values in the region and annual yield values, especially in terms of seed development stage and heading stage. Similar to wheat, a moderate negative correlation was found between the decrease in cool nights especially in June and yield in barley heading stage. During the phenological periods of barley, very high positive but statistically insignificant correlation relationships were identified between the yield values and the SPEI-6, prcptot, and rx5day indices, with correlations reaching up to 0.97. According to the coefficient of determination (r^2), although these correlations were insignificant, the rainfall-based indices explained 94% of the variance in annual barley yield. Specifically, the total precipitation (prcptot) and 5-day consecutive maximum rainfall (rx5day) values during November and December, corresponding to the sowing and seed development stages of barley, explained 60% of the variance in yield, while the harvest period (July-August) explained approximately 80% of the variance. In a study by Oosterom et al. (2009) in the Middle East, it was found that winter precipitation accounted for 61.8% of the variance in barley yield. According to the index calculations, there is a strong positive correlation between the decrease in rainfall values in Burdur and annual barley yields.

The correlation relationships between the annual wheat yields in Isparta province and the extreme index values obtained from the Isparta meteorological station are presented in Table 7.

Statistically significant weak-to-moderate correlation relationships, ranging from -0.39 to 0.33, were identified. According to the coefficient of determination (r^2), extreme index values explain between 10% and 15% of the variance in the annual wheat yield.

Among the extreme indices showing a significant upward trend in terms of climatic statistics, the following exhibited a positive correlation with annual wheat yield data: absolute maximum temperature (txx) for December; average minimum temperature (tnm) for June and July; and hot days (tx90p). On the other hand, among the extreme indices showing a significant downward trend in terms of climatic statistics, the cool nights (tn10p) index for June; and the daily temperature range (dtr) indices for February and June exhibited a negative correlation with annual wheat yield data.

Decreases in daily temperature range and increases in night temperatures were found to have negative correlations with annual wheat yield, particularly during the seed development and heading stages. Increases in minimum temperatures also showed weak but significant correlation relationships during the heading stages.

The correlation relationships between the annual barley yields in Isparta province and the extreme index values obtained from the Isparta meteorological station are presented in Table 8.

Table 7. Correlation coefficients between extreme indices and annual wheat yield in Isparta province

Phenological Stages	Indices Months	txm	txx	tnm	tnn	tn10p	tx90p	dtr	fd	spei6	prcptot	rx5day
Sowing	**Oct**	-0.10	0.08	0.24	0.23	-0.16	-0.13	-0.29	-0.04	0.28	0.13	0.23
	Nov	0.21	-0.07	0.01	0.07	-0.06	0.16	0.26	0.03	0.24	0.02	0.22
Seed Development Stage	**Dec**	0.21	**0.33**	0.00	-0.22	0.01	**0.31**	0.24	0.05	0.07	-0.14	-0.17
	Jan	0.00	0.21	0.01	-0.27	0.05	0.19	-0.02	0.02	0.03	0.10	0.12
	Feb	-0.10	-0.04	0.14	0.03	-0.10	-0.13	**-0.33**	-0.16	0.04	0.08	0.02
	Mar	-0.17	-0.08	-0.10	-0.15	0.30	-0.07	-0.16	0.20	0.04	0.02	-0.04
	Apr	-0.09	-0.08	0.18	0.01	-0.02	-0.13	-0.26	-0.05	0.05	0.02	0.02
Heading	**May**	-0.04	-0.03	0.11	0.19	-0.12	-0.02	-0.16	-0.12	0.06	0.05	0.13
	Jun	0.06	-0.15	**0.33**	0.21	**-0.36**	0.05	**-0.39**	-	0.23	0.10	0.15
Harvest	**Jul**	0.17	0.10	**0.32**	0.28	-0.28	-0.04	-0.21	-	0.21	0.13	0.20
	Aug	0.17	0.23	0.26	0.11	-0.29	0.20	-0.13	-	0.16	0.15	0.23
Annual Indices	**gsl**: 0.35		**csdi**: -0.29		**wsdi**:0.19							

Table 8. Correlation coefficients between extreme indices and annual barley yield in Isparta province

Phenological Stages	Indices Months	txm	txx	tnm	tnn	tn10p	tx90p	dtr	fd	spei6	prcptot	rx5day
Sowing	**Oct**	-0.15	0.05	0.11	0.07	-0.05	-0.13	-0.25	0.08	0.24	0.15	0.27
	Nov	0.13	-0.04	-0.04	0.03	-0.02	0.01	0.20	0.14	0.21	0.00	0.18
Seed Development Stage	**Dec**	0.25	**0.33**	0.05	-0.27	-0.02	0.26	0.23	0.03	0.09	-0.11	-0.08
	Jan	0.13	0.26	0.17	0.03	-0.12	0.20	-0.11	-0.10	0.07	0.04	0.09
	Feb	-0.17	-0.14	-0.01	-0.04	-0.02	-0.14	-0.25	0.01	0.08	0.12	0.12
	Mar	-0.14	-0.08	-0.11	-0.17	0.30	-0.03	-0.10	0.19	0.07	-0.08	-0.05
	Apr	-0.19	-0.04	0.18	-0.04	-0.03	-0.26	**-0.38**	-0.03	0.09	0.23	0.13
Heading	**May**	-0.01	-0.14	0.12	0.23	-0.12	-0.03	-0.12	-0.07	0.09	0.03	0.09
	Jun	0.04	-0.07	0.28	0.17	-0.30	-0.10	**-0.34**	-	0.23	0.01	0.10
Harvest	**Jul**	0.08	0.05	0.18	0.12	-0.12	-0.02	-0.14	-	0.21	0.00	0.07
	Aug	0.08	0.25	0.17	0.02	-0.16	0.20	-0.13	-	0.16	0.11	0.16
Annual Indices	**gsl**: 0.08		**csdi**: 0.12		**wsdi**: -0.11							

Statistically significant weak-to-moderate correlation relationships, ranging from -0.38 to 0.33, were identified. According to the coefficient of determination (r^2), extreme index values explain between 10% and 14% of the variance in annual barley yields. Among the extreme indices showing a significant upward trend in terms of climatic statistics, the absolute maximum temperature (txx) for December exhibited a positive (same-direction) correlation with annual barley yield data. On the other hand, among the extreme indices showing a statistically insignificant downward trend, the daily temperature range (dtr) for April and June exhibited a negative correlation with annual barley yield data. This means that as the daily temperature range decreases, barley yield shows an increasing trend. In a study by Vogel et al. (2019), it was found that extreme weather events and average climatic conditions in Europe had an impact of 8-28% on spring wheat yield variance. The study indicated that irrigation and agricultural techniques mitigated the negative effects of climatic extremes on yields; however, in areas with weak irrigation, extreme temperatures had more adverse effects on yields. Significant yield reductions require prolonged periods of drought and heat (Troy et al., 2015). For instance, in Burdur, severe droughts occurred in 1989 and 2007, leading to significant yield reductions

(Figure 2.5). Furthermore, the strong influence of the El Niño-Southern Oscillation (ENSO) led to significant yield declines in 1997 and 2015-2016 (Uzun & Ustaoğlu, 2022). Similarly, in Burdur, wheat and barley yields also experienced declines in 1997 and 2015. Extreme temperatures during the heading and flowering stages create heat stress on wheat and barley, reducing grain number and weight, leading to yield losses (Harkness et al., 2020).

Correlation Analysis Results Between Extreme Indices with Orange and Olive Yields

The correlation relationships between the annual orange yields in Antalya province and the extreme index values obtained from the Finike meteorological station are presented in Table 9. Statistically significant moderate to strong correlation relationships, ranging from -0.76 to 0.87, were identified. According to the coefficient of determination (r^2), extreme index values explain between 57% and 75% of the variance in annual orange yields.

Among the extreme indices showing a significant upward trend in terms of climatic statistics, the average maximum temperature (txm) for all months except June and October; the absolute maximum temperature (txx) for June; the average minimum temperature (tnm) and absolute minimum temperature (tnn) for all phenological months/stages; the hot days (tx90p) for August; and the 5-day consecutive rainy days (rx5day) for September exhibited moderate to strongly positive (same-direction) correlations with annual orange yield data. While the region shows a tendency for increased humidity based on the SPEI-6 index, moderate positive correlations were found between the indices for September and October and yield data. Among the extreme indices showing a significant or insignificant downward trend, the cool nights (tn10p) and the daily temperature range (dtr) indices for all phenological stages, except November, exhibited moderate negative (opposite-direction) correlations with annual orange yield data.

Table 9. Correlation coefficients between extreme indices and annual orange yield in Antalya province

Fenolojik Evreler	Indices Months	txm	txx	tnm	tnn	tn10p	tx90p	dtr	fd	spei6	prcptot	rx5day
Flowering	**Apr**	**0.38**	0.31	**0.72**	**0.63**	**-0.53**	0.22	**-0.40**	-	0.05	0.04	-0.03
Fruit Set	**May**	**0.34**	0.17	**0.78**	**0.80**	**-0.56**	0.27	**-0.66**	-	0.16	0.06	0.01
Fruit Growth Stage	**Jun**	0.31	**0.39**	**0.85**	**0.67**	**-0.65**	0.23	**-0.71**	-	0.19	-0.04	0.00
	Jul	**0.33**	0.10	**0.87**	**0.83**	**-0.56**	0.19	**-0.77**	-	0.23	-0.10	-0.16
	Aug	**0.45**	0.28	**0.87**	**0.87**	**-0.56**	**0.36**	**-0.76**	-	0.22	-0.13	-0.17
	Sep	**0.33**	0.17	**0.85**	**0.80**	**-0.52**	0.21	**-0.68**	-	**0.53**	0.30	**0.35**
	Oct	0.19	-0.07	**0.71**	**0.53**	**-0.56**	-0.08	**-0.59**	-	**0.57**	0.23	0.19
Harvest	**Nov**	**0.45**	0.27	**0.63**	**0.46**	**-0.47**	0.24	-0.22	-	0.31	-0.16	-0.11
Annual Indices	**gsl**: -0.16		**csdi: -0.56**		**wsdi**: 0.22							

Positive correlation relationships between annual orange yield and average maximum (txm), minimum (tnm), and absolute minimum (tnn) temperature values were found across all phenological stages. On the other hand, negative correlations were observed between cool nights (tn10p) and daily temperature range (dtr) with annual yield across all phenological stages. In the region, generally, increasing minimum and maximum temperatures, rising nighttime temperatures, and decreases in the daily temperature range have positive effects on yield under effective irrigation and proper agricultural practices. It was found that especially minimum temperatures were effective and related on the annual variances in orange yield. Increasing drought conditions (spei-6) toward the end of the fruit development stage (September, October) affect yield variations, but negative impacts can be mitigated with effective irrigation.

The main reason for the decline in citrus yields is soil erosion caused by extreme rainfall and excessive precipitation (Duan et al., 2020). On the other hand, a decrease in daily temperature differences during the fruit development stage, increased rainfall and humidity towards harvest, and the convergence of minimum and maximum temperature values are among the most important factors in increasing yield and product quality (Wang et al., 2022). Based on the correlation relationships, it is believed that the increase in minimum temperatures and the reduction in the daily temperature range contribute to the increase in orange yield in the region. The growth of citrus trees is limited by low temperatures and frost events (Balfagón et al., 2022). In Antalya, values related to frost days did not show a correlation with orange yield.

The correlation relationships between the annual olive yields in Antalya province and the extreme index values obtained from the Antalya Airport Meteorological Station are presented in Table 10.

Table 10. Correlation coefficients between extreme indices and annual olive yield in Antalya province

Phenological Stages	Indices Months	txm	txx	tnm	tnn	tn10p	tx90p	dtr	fd	spei6	prcp tot	rx5 day
Flowering	**Apr**	0.16	0.05	**0.49**	0.27	**-0.47**	-0.01	**-0.32**	-	0.11	0.11	0.19
	May	0.22	0.08	**0.43**	**0.45**	**-0.54**	0.12	-0.27	-	0.11	0.11	0.14
Fruit Set and Growth Stage	**Jun**	**0.40**	**0.36**	**0.60**	**0.36**	**-0.58**	0.29	-0.24	-	-0.07	-0.07	0.16
	Jul	**0.35**	0.04	**0.57**	**0.48**	**-0.56**	0.30	-0.20	-	-0.16	0.12	0.12
	Aug	0.29	0.28	**0.70**	**0.48**	**-0.63**	**0.44**	**-0.50**	-	0.02	-0.16	-0.01
	Sep	0.16	0.08	**0.54**	**0.32**	**-0.52**	0.03	**-0.44**	-	**0.39**	0.02	**0.37**
Maturity and Harvest	**Oct**	0.09	-0.08	**0.51**	**0.36**	**-0.45**	-0.03	**-0.52**	-	0.30	**0.39**	0.07
	Nov	**0.35**	0.24	0.27	0.12	-0.24	0.31	0.14	-	-0.11	0.30	-0.24
	Dec	-0.27	-0.26	-0.27	-0.27	-0.28	-0.23	-0.27	-0.17	-0.10	-0.11	-0.11
Annual Indices	**gsl**: -0.06			**csdi: -0.47**	**wsdi**: -0.03							

Statistically significant moderate to strong correlation relationships, ranging from -0.63 to 0.70, were identified. According to the coefficient of determination (r^2), extreme index values explain between 40% and 49% of the variance in annual olive yields. Among the extreme indices with a significant upward trend in terms of climatic statistics, the average maximum temperature (txm) for June, July, and November; the absolute maximum temperature (txx) for June; the average minimum temperature (tnm) for all months except November and December; the absolute minimum temperature (tnn) for all months except November, December, and April; the hot days (tx90p) for August exhibited moderate to strong positive correlations with annual olive yield data.

In terms of climatic statistics showing a significant or insignificant downward trend, cool nights (tn10p) for all months except November and December; the daily temperature range (dtr) for all months except April, August, September, and October; and the cold spell duration index (csdi) for all months except November exhibited moderate negative correlations with annual olive yield data. The region, according to the SPEI-6 index, shows a tendency for increased humidity, and moderate positive correlations were found between the indices for October and olive yield data. Among the indices with a significant or insignificant downward trend, the total precipitation for October (prcptot) and the 5-day consecutive maximum rainfall (rx5day) for September exhibited positive correlations with olive yield data. This suggests a weak relationship between the fluctuations in olive yield and the reduction in rainfall. However, the phenomenon of "periodicity," where olive trees do not fruit or fruit sparsely in alternate years, may also influence this relationship.

Moderate to strong positive correlation relationships were found between annual olive yield and average (tnm) and absolute minimum (tnn) temperature values across all phenological stages, including fruit ripening and harvest periods. On the other hand, moderate negative correlation relationships were identified between annual olive yield and cool nights and daily temperature range.

As temperatures rise in the region, moderate negative relationships were detected between the decreasing cold period durations (csdi) and annual orange and olive yields. Furthermore, this situation reduces the negative impacts of cold events such as frost during the winter season. However, due to the increasing temperatures, both crops may not be able to reach their chilling requirements in the winter season, especially the flowering periods may be damaged and the yield may decrease.

Rising temperatures projected in climate scenarios are creating stress on olive-growing areas. Temperature increases in the 21st century are expected to have detrimental effects on olive tree growth in the Mediterranean Basin. Extreme temperature values showing a linear trend during phenological periods lead to reductions in fruit size and oil quality (Kaniewski et al., 2023). In a study conducted by Uzun and Ustaoğlu (2022) in the Eastern Mediterranean, it was noted that olive trees are highly sensitive to rainfall during flowering and fruit development stages, with reduced rainfall during these periods leading to decreases in yield and fruit size. The study also mentioned that a reduction in total rainfall in October negatively affects olive yields. In this study, positive correlations were found between reduced total rainfall in October and 5-day consecutive maximum rainfall values and olive yields in Antalya. Reduced rainfall during the olive fruit development and ripening stages is particularly influential on yield. Another significant factor threatening olive yield, like other agricultural products, is the increase in diseases and pests (Caselli & Petacchi, 2021).

Conclusions and Recommendations

This study analyzed the relationships between annual yields of wheat and barley (Burdur-Isparta) and orange and olive (Antalya) crops and extreme temperature and precipitation events from 1980 to 2019 using correlation analyses. Most agricultural yield studies typically focus on average values, often overlooking the impacts of extreme temperature and precipitation events on seasonal yield variations.

Extreme weather events explain 10-33% of the variability in wheat and barley yields in Burdur and 10-15% in Isparta. In Burdur, increase in the length of the warm period, decrease in the length of the cold period, longer growing season, and reduction in frost days are favorable developments for agricultural yields. Although irrigation practices can mitigate yield losses in cereal crops, increasing occurrences of sudden heatwaves and agricultural drought conditions, as well as the rapid depletion of water resources, remain key threats to agricultural productivity and sustainability. Furthermore, heat stress in plants accelerates growth during the seed development and heading stages, which can reduce grain yield.

Although statistically insignificant correlation results were found, it was observed that barley yield is more susceptible to variations in rainfall, particularly in Burdur, compared to wheat yield. Trends in precipitation were found to be 80 to 90 percent correlated with barley yield variances. In general, the relationships between extreme events and grain yield were found to be stronger in Burdur than in Isparta. Weaker agricultural drought conditions in Isparta, fewer frosty days, lower daily temperature ranges, more favourable agricultural irrigation resources and sufficient rainfall values can be shown as reasons for this situation. Due to increased variability in extreme precipitation values and seasonal shifts in precipitation, anomalies detected during cereal development periods in terms of phenological periods are predicted to increase. Although the risk of crops being affected by extreme cold decreased in both regions, the relationship between extreme temperatures and yield variances increased. Increasing temperatures during the seed development and spike stages of the crops pose a serious threat; considering the severe evaporation and level drops in water resources, proper water management and planned irrigation activities are important.

One of the most important results of the study is that especially the minimum temperatures, which increased the most in the region, significantly reduced the cool nights, the duration of the cold period and the daily temperature differences. This explains 60% of the variances in orange yield (fruit set and developmental stage) and 75% of the highest significant/strongest correlation relationships. The reduced risk of agricultural frost in the region creates favourable opportunities for orange yields. On the other hand, increasing extreme temperatures and sudden heat waves in spring and summer (developmental stage) cause fruit development to stop and thus yield losses. In coastal areas, periodic spikes in temperature gave stronger relationships in terms of yield reduction rather than agricultural drought conditions. In addition, the increase in all average and extreme precipitation index values is predicted to cause floods and overflows in the region, increasing the damage to orange trees and other agricultural lands.

For olive trees in Antalya, the impact of increased minimum temperatures, shortened cold periods, fewer cool nights, and reduced daily temperature range is similar to the effects observed in oranges. Minimum temperature values explained 50% of the yield variance, especially during the fruit formation and development phase (summer and autumn months). Sudden temperature increases in spring and summer months decrease fertilization and fruit set. According to the results of SPEI-6 index, it was determined that there is a significant tendency of drought in Antalya province center and east. Especially drought values in September (olive development stage), which comes immediately after the dry summer months, explain 15% of the yield variance. Drought conditions prevent adequate ripening of olives and negatively affect olive yield and quality.

Considering the increasing frequency of extreme weather events due to the changing climate, it is anticipated that agricultural productivity and product quality will be further impacted in the coming years. Provided that necessary adaptation measures are implemented, the advancements in technology and improved agricultural systems can not only mitigate the adverse effects but also allow us to leverage the opportunities presented by climate change to enhance yield and production values. Extreme weather events significantly influence crop yield, harvest quantity, and quality during critical phenological periods, while also directly affecting seasonal product prices from an economic perspective. Future studies should focus on conducting ecological, phenological, and socio-economic analyses of the impacts of climate change on agriculture. These investigations should examine the climatic requirements of crops during their phenological stages, assess extreme threshold values, and emphasize national risk assessments to inform adaptive strategies.

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Ethical Approval

No need to ethical approval for this study.

Conflicts of Interest

The author declares that they have no conflict of interest.

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