Black Sea Journal of Agriculture
doi: 10.47115/bsagriculture.1860873

Open Access Journal
e-ISSN: 2618 – 6578

Research Article
Volume 9 - Issue 3 : 431-448 / May 2026

HETEROGENEOUS IMPACTS OF CLIMATE CHANGE ON FRUIT PRODUCTION: EVIDENCE FROM TÜRKIYE USING PANEL DATA ANALYSIS

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Abstract: The effects of global climate change in our country have begun to be felt in many economic and social sectors. The sector that is most sensitive to climate is the agricultural sector. The discussions on plant production, food security, and access to them, which are a part of the agricultural sector, have started to increase in our country as in other countries. Agricultural production in Türkiye is still under the influence of climatic conditions compared to developed countries. A change in climate elements continues to directly affect agricultural production. Climate change research generally states that the Mediterranean, the Middle East, and North Africa, including Türkiye, are the regions most affected by climate change. This study investigates the effect of global climate change on fruit production in Türkiye. The data source of the study is the production of 63 fruits obtained from TURKSTAT between 2004 and 2024 and the annual averages of temperature and precipitation taken from Meteorology between the same years. These data were analysed using the panel fixed effects method in the Python 3.12 program and statistically significant and insignificant results were obtained. As a result of the study, it was determined that 5 fruit species (Orange Washington, Portal Yafa, Tangerine, Blueberry and Carob) showed a significant change due to the increase in temperature, 10 fruit species (Avocado, Fig (Fresh), Apple (Starking), Other Apples, Nectarine, Plum, Blueberry, Almond, Carob, Pomegranate) were significantly affected by precipitation, some fruit species increased yields up to a certain temperature and their yields started to decrease after the limit temperature was exceeded, some fruits did not establish a significant relationship with temperature and precipitation, and some of them decreased their yields due to the decrease in precipitation as the temperature increased. In general, it has been determined that the changes in temperature and precipitation in Türkiye due to global climate change have affected the yield obtained per decare positively in some products and negatively in others. The research suggests that agricultural areas in Türkiye should be used in a more conscious and sustainable way and that a faster transition to an intensive agricultural system should be made, where climate conditions are less effective and modern agricultural methods are applied, as in developed countries.

Keywords: Global climate change, Fruit production, Agricultural geography, Climate-agriculture relationship, Panel data analysis

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Received: January 11, 2026
Accepted: May 08, 2026
Published: May 15, 2026

Cite as: Özcanlı, M. (2026). Heterogeneous impacts of climate change on fruit production: Evidence from Türkiye using panel data analysis. *Black Sea Journal of Agriculture*, 9(3), 431-448.

1. Introduction

Climate change is the most important result of the greenhouse effect, which has been strengthened as a result of the rapid increase in greenhouse gases in the atmosphere due to many human activities since the Industrial Revolution, creating an additional positive accumulation on the earth's energy balance and making the world's climate warmer (Türkeş, 2012). Today, global climate change has become one of the biggest obstacles to global food security. Global climate change has become a serious threat to agricultural production by affecting world food production. The world needs more food production for its rapidly growing population. With the increasing demand pressure of the rapidly growing population, agricultural systems need to take sustainable measures to meet the increasing food demand. The effects of climate change on agricultural production processes are complex. Unfortunately, this situation is complicated by the increasing human pressure on natural resources and the uncertain effects of climate change on global agriculture. Agricultural product production, which is under the influence of many different variables, is often very difficult to measure when different variables come together. In general, climate change includes, but is not limited to, changes in atmospheric CO_2 concentration, air temperature and precipitation dynamics, which are vital for agricultural production (Bondeau et al., 2007; Kothiyal et al., 2024; Zambrano-Medina et al., 2024).

Due to anthropogenic effects, the world surface temperature increased by 1.1 °C between 2011-2020 compared to the temperature accumulation between 1850-1900. The main reason for this is greenhouse gas emissions. Global greenhouse gas emissions continued to

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increase between 2010 and 2019. Compared to the previous period, the use of fossil fuel-based energy, misuse of land and increase in artificial space in land use, lifestyles, consumption and production patterns between regions, between countries and within countries and between individuals have not changed and even increased in some regions (IPCC, 2024).

Human-induced climate change is already affecting many weather and climate extremes in every region of the world. These extreme weather events have caused and continue to cause widespread adverse effects on nature and people, food and water security, human health, economies and society, and associated losses and damages. One of the most tragic consequences of this situation is that vulnerable communities that have historically caused the least climate change are disproportionately affected (IPCC, 2024).

Exceeding the average temperature level in the world causes more irreversible adverse effects and additional risks for human and natural systems compared to staying below that level of warming. The risks of global average temperature increase increase with the magnitude and duration of the exceedance. When the irreversible threshold is exceeded, communities and ecosystems will be exposed to larger and more widespread changes, such as climatic events such as extreme temperatures and extreme precipitation. This will pose increased risks to urban infrastructure, low-lying coastal settlements, economic activities, agricultural land and associated livelihoods. At the same time, exceeding 1.5 °C in the global average surface temperature will lead to irreversible adverse effects on certain low-resistance ecosystems, such as polar, mountain and coastal ecosystems affected by glacial sheet melting, glacial melting or accelerated and higher stable sea level rise. Exceeding this temperature threshold will increase the risk of serious impacts such as increased forest fires, mass deaths of trees, drying of peatlands, thawing of permafrost and weakening of natural land carbon sinks (IPCC, 2024).

Due to global climate change, the temperature in each 10 years from 1990 to 2020 has been warmer than in any 10 years since 1850. According to the average surface temperature measurement results on the earth's surface, a linear increase of 0.89 °C was observed in the 1900 – 2010 period. In this 110-year period, the entire world's surface and atmosphere have warmed up, especially since the 1950s, including the Troposphere, the lowest layer of life and our atmosphere. In the IPCC (2024) report, the anthropogenic global warming value reached approximately 1.14 °C in the calculations including the updated surface temperature observations in 2020. In addition, recorded historical climate data shows that the 1983-2012 period in the Northern Hemisphere of our Earth was most likely the hottest 30-year period of the last 1400 years. In this recent past, heat accumulation in the atmosphere and oceans has increased, snow and ice deposits have decreased, average sea level has risen, and the rates of carbon dioxide and similar gases in the atmosphere have increased (Türkeş, 2020).

The results of the heat accumulation in the 1900 - 2012 period in global climate change did not have the same effect in all regions of the world. There is a high spatial and temporal variability in the regions around the world. While precipitation amounts at the regional level tend to increase in some regions, it has been observed that they tend to become arid in some regions (Calvin et al., 2023). This variability is present in the hemispheres of the world. In the Northern Hemisphere, an increase in precipitation has been observed in the last century, especially in the lands (Jha et al., , 2004). Looking at the precipitation graphs for many years in the north of the continent with the coasts of the American continent (North and South) facing the Atlantic Ocean, the north of the European continent and the middle parts of the Asian continent, significant increase trends have been observed. There are regions where this situation is in the opposite direction, and significant drought or precipitation decrease trends have been effective in the Mediterranean basin, including Türkiye, a part of South Asia and the south of Africa (Türkeş, 2020; Yate and Ren, 2025).

Significant increases have been recorded in average temperature values in many regions of the world and in Türkiye. This was followed by excessive precipitation and severe drought events. (IPCC, 2013; Türkeş and Erlat, 2018). As in many parts of the northern hemisphere, the changes in precipitation in our country are in the form of significant changes in the shortening and severity of the intermediate periods in the alternation of dry and humid periods with different forms of change and fluctuation rather than long-term records (Tatlı and Türkeş, 2011; Şen et al., 2013; Çaltı and Somuncu, 2019; Özuyar et al., 2021). The regional variability of precipitation changes (minus/plus) in Türkiye is also quite evident. For example, the tendency of aridity due to the decrease in the amount of precipitation is mostly observed in the Aegean, Mediterranean, Marmara, Central and Southeastern Anatolia regions in our country (Türkeş, 2012; Kapluhan, 2013; Akbaş, 2014).

The most important problem faced by Türkiye's agriculture is related to insufficient rainfall and drought. In line with global climate change reports, it is expected that arid areas will expand and desertification will increase in our country as well as in the world (Koçman, 1993). This situation poses a great risk on the existing agricultural areas. 89% of Türkiye's territory is at risk of desertification (Varol and Ayaz, 2012). This is both a critical and alarming prediction for our country. Türkiye is under the threat of desertification and drought due to both its climatic characteristics and topographic structure. For these reasons, Türkiye is among the critical countries in terms of desertification (Karataş, 2024). In addition, Türkiye is a poor country in terms of water resources; the amount of water per capita is

approximately 1400 cubic meters. The world average is around 7600 cubic metres per year. Forecasts indicate that the amount of water per capita in Türkiye will decrease to 1000 cubic metres by 2030 due to the increasing population (Karşili, 2011). This situation creates a very critical safety threshold and requires the management of water resources in an extremely careful and sustainable manner (Özkan et al., 2013).

Temperatures in Türkiye are increasing regularly every year. The frequency, duration and severity of heat waves, which occur with high temperature and humidity, have increased especially in summer. The increase in night temperatures enlarges the heat islands in cities and the resulting thermal stress becomes a factor that directly threatens life (Şenlik and Yılmaz, 2023). A continuous decrease has been observed in the amount of precipitation from the past fifty years to the present; it is expected that the amount of precipitation will decrease by approximately 20% throughout the country. Although there has been an increase in precipitation in certain periods in recent years, the general trend is that precipitation will decrease (Yılmaz, 2021). While an increasing trend was observed in the daily maximum and minimum temperature values of 165 stations throughout Türkiye for the years 1961-2008, a decreasing trend was observed in the daily maximum and minimum temperature differences (Environment and urbanisation /climate change 6th In 2009, temperatures were recorded 0.90 °C above seasonal normals and precipitation increased by 20% compared to the previous year. Similarly, in 2010, temperatures were 2.39 °C above seasonal norms and precipitation increased by 16.3% compared to the normal level and by 4.8% compared to last year's precipitation (Varol and Ayaz, 2012). However, as of 2011, while temperatures were around seasonal normals, precipitation generally exceeded normals but remained below the level of the previous year. As can be understood from these data, the climate of our country exhibits serious changes in terms of temperature and precipitation parameters (Tümertekin, 1957; Tümertekin, 1987; Bayar, 2004; Nacar et al., 2024).

Changing climate conditions across Türkiye will create regional differences and this process will directly affect the country's water resources, natural vegetation, agricultural production capacity, human health and overall quality of life. With climate change, the risk of forest fires will increase, and the increase in the insect population will negatively affect the food chain and other living populations (Akalın, 2014). Diseases and health problems will become widespread; some living species will face the threat of extinction (Özcanlı and Yılmaz, 2024). The decrease in the flow values of the rivers will lead to a decrease in energy production and increase the energy deficit. Temperature values increasing with drought will also negatively affect tourism activities. Decreasing water resources and problems that may arise in the sharing of these resources may lead to tense relations between Türkiye and neighbouring states. These processes, which are generally experienced, have clearly shown that climate change and drought will have serious effects on Türkiye. In this context, it is clear that radical changes should be made in the consumption of energy, water and other natural resources. It is vital to be careful, conscious and sensitive in resource management. For example, the average temperature in 2010 was +2.39 °C higher than the average of 1971-2000 and was recorded as the hottest year of the last decade (Varol and Ayaz, 2012).

After the drought that was effective throughout Türkiye in 2007-2008 and caused a serious water deficit, more humid and rainy climate conditions prevailed in the 2009-2011 period, generally above the average for many years. However, meteorological droughts, which started to show their effects again in 2012, especially in some parts of Central Anatolia and Eastern Anatolia, combined with summer drought, made 2013 quite dry for a large part of Türkiye. This drought has had an impact ranging from moderate to extraordinary levels, especially in the Central and Eastern Anatolia regions and in areas such as the Central and Eastern Mediterranean, Eastern Marmara and Central Black Sea. As a result, the cumulative amount of precipitation recorded throughout Türkiye between 1 October 2013 and 17 January 2014 decreased by 37% compared to the average of many years and by 47.4% compared to the same period of the previous year (Türkeş and Erlat, 2018). When the 2013-2014 drought is evaluated according to the Standardized Precipitation Index (SPI) calculations covering 6 months or longer, it is no longer just a meteorological drought; it has become a serious problem that brings along agricultural and hydrological droughts (Şahin 2001; Bozkurt et al., 2008; Türkeş, 2012).

The increase in the accumulation of greenhouse gases in the atmosphere will lead to serious changes in climatic variables such as surface temperatures, lower troposphere temperatures, evaporation, clouding, precipitation and humidity, both on a regional and global scale. Global and regional climate modelling studies conducted in Türkiye and its surrounding regions predict that there will be decreases in precipitation (especially rain and snow) in our country in the future; on the other hand, there will be an increase in air temperatures, evaporation, and the frequency and severity of heat waves. In addition, it is estimated that drought events will become longer and more effective. These projections show that agricultural activities in Türkiye may be adversely affected by climate change, like many countries in the Mediterranean basin (Uslu, 2021). Accordingly, it is critical for Türkiye to accurately predict future climate conditions in order to prevent or minimise the effects of climate change and to adapt to the changes that will occur. (Temuçin, 1993; Wur et al., 1996; Başoğlu and Telatar, 2013; Banias et al., 2017).

Carbon dioxide (CO_2) and other greenhouse gases, which began to be released into the atmosphere with the

Industrial Revolution, trapped the long-wavelength rays reflected from the Earth and caused the average surface temperatures to rise significantly. This is called the natural greenhouse effect (Doğan, 2005; Akın, 2006). As a result, the increase in temperature in the lower layers of the earth and atmosphere has triggered global warming, and this process continues to accelerate today (Atabay et al., 2014). According to the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), According to the Assessment Report, climate changes observed since the 1950s have reached an unprecedented level in the last thousand years. The report also states that the 1983-2012 period in the Northern Hemisphere was recorded as the hottest 30 years of the last 800 years (IPCC, 2013). Current research reveals that global warming has reached 1.064 °C by analysing the changes in global surface temperatures.

According to the special report published by the IPCC in 2018, limiting the global temperature increase to 1.5 °C instead of 2 °C will significantly reduce climate-related risks on human and natural ecosystems (IPCC, 2024). In terms of climate change, it is predicted that the increase in temperatures and the decrease in precipitation patterns will seriously affect Mediterranean agriculture, which has a sensitive structure and is largely based on irrigation (IPCC, 2013). Although agricultural activities are largely under human control, they have not been fully adapted to changing climatic conditions in many regions. This situation is expected to adversely affect food supply and prices with the effect of climate change, make it difficult for low-income societies to access sufficient food, and consequently create significant problems in terms of food security (Lelieveld et al., 2012; Türkeş, 2020).

Ensuring sustainability and supporting food security against the potential effects of climate change is therefore an important requirement for the wide range of fruit-derived products in Türkiye, including table grapes, raisins, wine, grape juice, verjuice, molasses, and fruit pulp.

The link between climatic stress and fruit production has also attracted growing attention in the wider international literature. Highly-cited Web-of-Science-indexed studies report that rising temperatures and shifting precipitation regimes are reshaping the phenology, yield potential, and geographic suitability of major perennial fruit crops at a global scale (Schlenker and Roberts, 2009; Lobell et al., 2011; Iglesias and Garrote, 2015; Yang et al., 2024). The Mediterranean basin, of which Türkiye is a constituent part, is consistently identified in these works as one of the most climate-vulnerable horticultural regions of the world, which further motivates the country-level empirical exercise undertaken here.

Plant development in the middle latitudes is largely dependent on air temperature. Plants that wake up from hibernation in the spring move their phenological stages to earlier periods with increasing temperatures. It is stated that the significant temperature increases observed worldwide, especially since the 1980s, have had significant effects on plant phenology. When considered in the context of Türkiye, it is thought that the significant temperature increases recorded after the 1990s brought forward the phenological processes of agricultural products and horticultural plants. Although temperature increases of up to one degree in human life usually lead to small-scale changes, such a difference in plant development can have quite large consequences. For example, such a temperature increase may correspond to a total of 60 degree-day effect associated with plant development over a period of only two months and lead to shifts in the timing of phenological periods. A climate index study in Türkiye shows that the duration of the growing season has increased by an average of 21 days in the last hundred years (Türkeş, 2020). In addition, it is stated that increasing temperatures have an accelerating effect on plant development in the mid-northern latitudes (Önol and Semazzi, 2009; Zittis et al., 2022).

Fruits are among the special structures formed by angiosperms to spread their seeds. Edible species play a critical role for living things by providing an important food source as well as facilitating the spread of seeds. This has paved the way for a symbiotic relationship between humans and animals; their movements have been an effective element in the transportation of seeds to large areas. In addition, humans and many animals have adopted fruits as one of their main food sources and have developed an addiction to them. For this reason, while fruits have an important place in agriculture, some species such as watermelon and orange have gained cultural and symbolic meanings and have found a special value in social contexts. The concept of fruit is handled in botany with both practical and academic perspectives. Such that, situations such as a flower producing more than one fruit or several separate flowers combining to form a single fruit are evaluated in this context (Ankara Üniversitesi, 2026).

Fruits are generally divided into two main groups: Fleshy and juicy fruits and dry fruits whose pericarp dries completely when ripe. Fruits, which stand out with their high fibre content, abundant vitamin C and antioxidant content, are also generally rich in sugar. However, some species, such as bananas, are noteworthy for potassium. In everyday use, when we say "fruit", we mostly think of structures such as apples, bananas, grapes, oranges, lemons and strawberries, which can be consumed raw with their sweet or sour aromas. However, the concept of fruit in botany is much broader. Bean shells, tomatoes, corn grains, wheat grains and even the "fruit-bearing body", which is the spore-producing part of mushrooms, are included in this definition. The distinction between fruit and vegetables often causes confusion. Fruit develops from the special reproductive tissues of flowering plants and usually contains reproductive organs and some supporting tissues. Vegetables, on the other hand, refer to the edible parts of the plant other

than the fruit. Fruits are generally distinguished from vegetables by their sweet properties; although species such as eggplant, pepper and tomato are botanically considered fruits, they are included in the vegetable category in the kitchen because they are not sweet. Leaves, tubers, shoots and flowers are among the other structures included in the vegetable group (Durmuş and Yiğit, 2006; Gerçekçioğlu et al., 2012; Durmuş and Yiğit, 2014; Sarıyer and Çolak, 2024).

The yield of fruit production by years is an important tool that can be used to assess the effects of climate change on the agricultural production system and to formulate adaptation measures for it. The introduction explained recent trends in greenhouse gases, precipitation, temperature, sea level and extreme weather events. The associated effects of these changes on food products are also briefly explained. In addition, the basics of fruit production and its applications in climate change studies and adaptation strategies have been tried to be given briefly.

The principal contribution of this paper is to provide, for Türkiye as a whole, a unified empirical characterisation of the relationship between nationwide climatic averages and overall fruit production for an unusually broad set of 63 fruit species, using a single, internally consistent panel covering the most recent two decades. To the best of the authors' knowledge, no previous study has jointly examined this many fruit species in a fixed-effects panel framework using harmonised national TURKSTAT data, which makes the analysis particularly informative for sector-wide policy discussions on climate adaptation in Turkish horticulture.

Based on the discussion above, the present study tests the following hypotheses at the national level for Türkiye over the 2004–2024 period: (H1) variations in nationwide annual mean temperature exert a statistically significant, non-linear (inverted-U-shaped) effect on aggregate fruit yield; (H2) variations in nationwide annual total precipitation exert a statistically significant, non-linear (U-shaped) effect on aggregate fruit yield; and (H3) the magnitude and direction of these climatic effects are highly heterogeneous across the 63 fruit species considered, so that aggregate findings necessarily mask species-specific responses that have to be characterised individually.

1.1. Literature Summary

In recent years, increasing awareness of global warming has led to a remarkable increase in studies addressing the relationship between climate change and the agricultural sector. However, it is observed that the effects of climate change on agriculture vary greatly depending on many factors such as the geographical characteristics of the countries, regional conditions and different seasonal dynamics. This necessitates the development of specific assessments and solutions for each region. Considering the important studies in this field, Şaylan (2021) stated that the agricultural sector is one of the areas most affected by climate change and emphasised the particular sensitivity of this sector to extreme weather events such as floods, storms, hail, drought and heat waves. Akyüz and Atış (2016) examined the effect of climate change on agriculture and the contribution of agriculture to this change through the example of Türkiye. Bayraç and Doğan (2016) tried to predict the potential effects of climate change on the sector by analysing the possible relationships between agricultural GDP and agricultural yield, CO_2 emission, temperature and precipitation amount with the ARDL model. Dinç et al. (2022) stated that production technologies should be changed and new product types suitable for regional conditions should be grown in order to ensure sustainability. Oğul (2022) stated that the increase in precipitation and humidity rates positively affected the share of the agricultural sector in GDP, while the increase in temperature, population density and CO_2 emissions negatively affected this share. Kara et al. (2019) emphasized the effect of differences in precipitation amounts in germination and growth processes as one of the reflections of climate change on plants. While Hayaloğlu (2019) stated that climate change affects not only agriculture but also economic growth, Duru (2025) tried to shed light on future expectations by discussing the concept of sustainable agriculture within the framework of climate change and food security. Korkmaz (2007) argued that global warming can seriously affect human health, various socioeconomic areas and ecological systems directly or indirectly by disrupting the natural balance. In recent evaluations, Nsabiyeze et al. (2024) examined the existing literature and data on agricultural carbon emissions in detail and investigated the potential of innovative technologies and reduction strategies. Yuan et al. (2024) aimed to provide scientific bases and recommendations to ensure the sustainable development of agricultural production. Qosimov and Imomov (2025) analysed in depth the main effects of climate change on crop yield. Plante et al. (2024) investigated the effects of climate change on agriculture through insect pests such as aphids; Verma et al. (2025) highlighted the role that interdisciplinary approaches and advanced technologies will play in overcoming these challenges. Finally, while Yang (2024) discussed the effects of climate change on agricultural sustainability and solution strategies for the problems encountered in this context, Parra-López et al. (2024) called for action for a more sustainable future. In this study, attention was drawn to the importance of multi-stakeholder collaborations in order to create a favourable environment for the adoption of innovations, to make innovations accessible, cost-effective and adaptable to different agricultural systems.

2. Materials and Methods

Study area. The empirical analysis covers the entire territory of the Republic of Türkiye, a country that lies between approximately 36°–42° N latitudes and 26°–45° E longitudes and that extends across multiple agro-

ecological zones, including Mediterranean, continental and humid temperate regimes. Türkiye is one of the few countries in the world where almost all temperate-zone fruit species as well as a meaningful share of subtropical species can be cultivated, which makes it a particularly informative setting for assessing the aggregate, country-level relationship between climatic conditions and fruit production. In line with the central aim of the study — which is to reveal the link between Türkiye's nationwide climate averages and overall fruit output— the analytical unit is defined at the national scale rather than at the provincial or regional scale.

The data, variables and econometric approach used to analyse the impact of global climate change on fruit production in Türkiye methodologically consist of the annual averages of temperature and precipitation obtained from Meteorology between 2004 and 2024, the same years as the production of 63 fruits obtained from TurkStat. These data were analysed using the panel fixed effects method in the Python 3.12 program and statistically significant and insignificant results were obtained.

2.1. Data and Variables

In this study, an annual balanced panel data set of 63 main fruit species in total was used, taking into account a period covering the years 2004-2024 throughout Türkiye. With the advantages provided by the panel data structure, it becomes possible to control fruit-specific characteristics that do not change over time but cannot be directly observed. Such characteristics often stand out as key factors affecting fruit production, such as genetic potential and soil quality. Therefore, panel data analysis isolates the effect of such factors and provides healthier and more reliable results. The main variables used in the analysis are:

- Yield: The output obtained per unit of cultivated land, measured in kilograms/decare (kg/decare). In order to allow for an elasticity-based interpretation and to stabilise the variance, the natural logarithm of this variable (lyield) was used as the dependent variable in econometric models.
- Decare (Planted Area): The total amount of land planted for each fruit type, measured in decares.
- Ton (Product Quantity): Indicates the annual production amount for each fruit type, measured in tons.
- Temperature: The annual average temperature, measured in degrees Celsius (C). This variable is included in the model in the form of a level.
- Precipitation: Total annual precipitation, measured in millimeters (mm). The natural logarithm of this variable (lPrecipitation) was used to capture the percentage-based effect of precipitation.

On non-climatic determinants of yield. The authors fully acknowledge that fruit yield is jointly determined by a wide set of agronomic factors that go beyond climate, including fertiliser use, irrigation regimes, planting techniques, rootstock and cultivar choice, plant-protection practices and post-harvest management. Comprehensive, species-level annual data on these inputs are, however, not systematically published by official statistical agencies for the full 2004–2024 window and for all 63 fruit species included in the panel. Within the fixed-effects panel framework adopted here, the species-specific intercepts (α_i) absorb time-invariant differences in such practices across fruits, while the species-specific OLS regressions further include a linear time trend that captures the long-run effect of gradually evolving production technologies, irrigation infrastructure and modern cultivation methods. The interpretation of the climate coefficients is therefore conditional on these absorbed factors.

Scope of the climatic variables. The temperature and precipitation series used in the empirical models are deliberately specified as nationwide annual averages. This choice is consistent with the central objective of the paper, which is to characterise the overall, country-level association between Türkiye's general climatic averages and aggregate fruit production. Replacing the national series with region-specific or growing-season-specific climatic indicators —while undoubtedly valuable in its own right— would shift the unit of analysis from the country to the producing region of each individual fruit and would, in effect, require a separate empirical study for each of the major fruit-producing regions of Türkiye. Such an extension would also enlarge the panel to several thousand additional observations, multiply the parameter space substantially, and turn the present aggregate exercise into a markedly different research question. For these reasons, the use of national climatic averages is retained here, while the construction of region- and phenology-specific climate indicators is identified as a promising direction for future, complementary research.

Justification of the 2004–2024 sample window. The lower bound of the sample period is dictated by data availability rather than by the authors' preference. The Turkish Statistical Institute (TURKSTAT/TÜİK), which is the only official source of crop-level fruit production statistics in Türkiye, publishes harmonised, species-disaggregated fruit production data starting from 2004; observations before that year are either unavailable for several of the 63 fruit species considered here or are reported under different aggregation schemes that are not directly comparable with the post-2004 series. Extending the panel backwards would therefore require either (i) dropping a substantial fraction of fruit species and reducing the cross-sectional dimension, or (ii) splicing a series of differing definitions, which would introduce measurement error of unknown sign and magnitude. Both options were judged to be more harmful to the reliability of the estimates than the use of the longest internally consistent panel currently available, namely 2004–2024.

2.2. Descriptive Statistics

In order to analyse the basic characteristics and general

trends of the variables more clearly, the emphasis was primarily on validation analysis. This approach was considered an important step to test the robustness of the data obtained and to achieve more consistent results.

In the light of the examinations carried out on descriptive statistics (Table 1), it has been determined that the variables of Yield, Ton and Decare in the panel data show a very high level of heterogeneity. This is clearly seen in the standard deviation values of the Yield and Decare variables. The standard deviation value of the Yield variable (SD=851.8) and the standard deviation value of the Decare variable (SD=1,255,378) reveal that both variables have a remarkably high variation compared to their averages (Bello and Maman, 2015). Panel data variables (yield, decare, ton) are specific to each fruit (Figure 1 and Figure 2).

Such observations indicate that the level of heterogeneity in the panel data set is quite evident. This high level of heterogeneity requires special attention and care when determining the methodological approach to be used in the analytical process. It has been evaluated that the results of simpler approaches, especially the Pooled Least Squares Method (Pooled OLS), which carry the risk of neglecting the structural differences between the data, may face statistical bias. It is thought that the Pooled OLS method may not adequately reveal the dependency effects between variables and errors may mislead the model (Schlenker and Roberts, 2009).

In this context, it was concluded that the Fixed Effects Panel Model (Table 2), which stands out among the alternative models suitable for panel data analysis, is the most appropriate method for the current analytical needs. The main advantage of the Fixed Effects Panel Model is its ability to control all variable differences specific to the fruit species analysed that remain constant over time. This model provides the opportunity to evaluate the heterogeneous structure in the data set and the relationship between variables in more depth, thus providing more reliable and robust results. Therefore, the preference of the Fixed Effects Panel Model within the scope of this study was seen as an important step in terms of analytical consistency. To formally justify this choice, a Hausman specification test was conducted for each of the three outcome equations. In all cases, the test statistic was statistically significant ($P<0.05$), decisively rejecting the null hypothesis that the individual effects are uncorrelated with the regressors and thus confirming that the Fixed Effects estimator is consistent while the Random Effects estimator would be biased. As a robustness check, the panel regressions were also re-estimated using cluster-robust standard errors at the fruit level (already applied), as well as an alternative specification excluding the quadratic precipitation term; the sign, magnitude and significance of the temperature coefficients remained qualitatively unchanged across specifications, lending additional confidence to the reported findings.

Table 1. Descriptive statistics

Variable	Number of Observations	Average Minimum	Std. Deviation	Minimum	Maximum
Panel Data Variables (i, t)					
Yield (tonnes/decares)	1.254	349.82	851.82	0	7191
Decare	1.254	544.958	1.255.378	0	7.497.692
Tonnes	1,254	340552.7	423863.4	0	2583682
Time Series Variables (t)					
Temperature (C)	21	11.92	0.87	10.74	13.62
Precipitation (mm)	21	697.43	70.44	541.09	823.38

Note: 1 Climate variables (temperature, precipitation) are annual national averages common to all fruits.

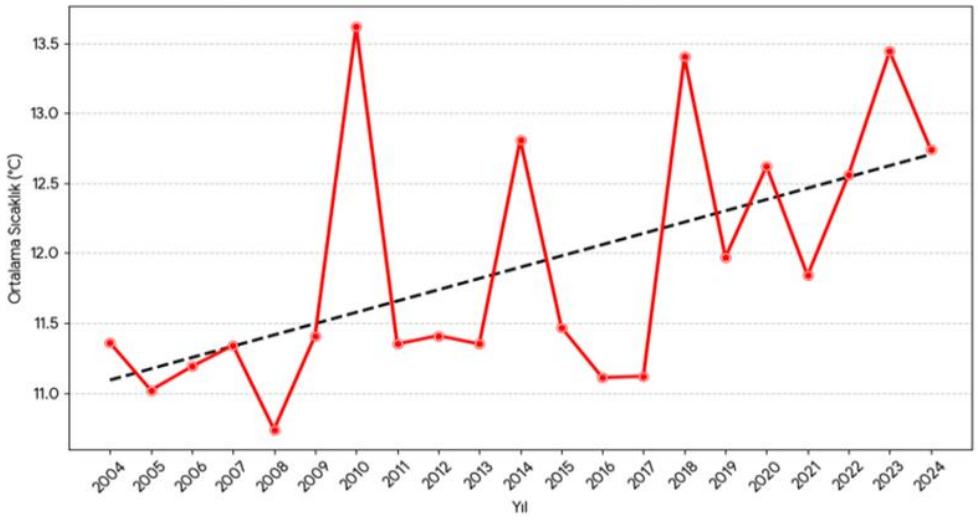


Figure 1. Graph showing the temperature increase trend in Türkiye between 2004 and 2024.

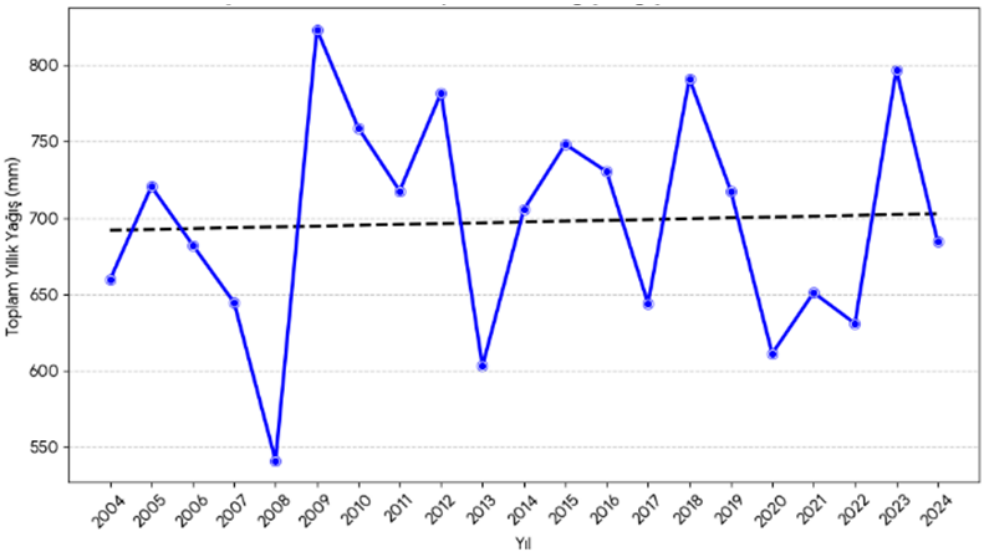


Figure 2. Graph showing the trend of annual average precipitation in Türkiye between 2004 and 2024.

2.3. Econometric Model

An analysis was carried out using the Fixed Effects Panel Data Model in order to understand the causal relationships of climate variables on fruit yield in a more detailed and comprehensive way, and also to make more accurate predictions for possible conditions that may be encountered in the future. The main reason for choosing this model is that it can include inter-species heterogeneity factors (αi) that remain constant throughout the process examined but cannot be directly observed or measured. Such heterogeneous elements may include environmental or biological factors such as the genetic diversity of the species concerned, the structural resilience of the soil, or their resistance to certain climatic conditions. In particular, the clear separation of these fixed elements during the modelling process significantly increased both the accuracy and reliability of the analysis results and laid a more solid ground for the findings of the study. This analytical approach also offers a significant advantage in examining the non-linear dynamics that can be observed in the relationships between climate variables and fruit yield. In this context, not only linear effects but also quadratic effects are included in the model based on logarithmic expressions of temperature changes and precipitation amounts. While these comprehensive additions broadened the perspective of the analysis process, they made it possible to reveal the effects of the variables examined on fruit yield in a more detailed and complex way. In particular, addressing the curvilinear and multidimensional effects of climate variables in such detail has given the study a significant depth and facilitated the critical evaluation of the results obtained.

In addition, thanks to the mathematical expressions presented below, a clear understanding of the practical use process of the technical structure of the Fixed Effects Panel Data Model is provided. These statements strengthen the scientific infrastructure of the study by contributing to a better understanding of the methodological stages (Equations 1-3).

It is explained that the expression ln(Yield it) in the formulation refers to the natural logarithm value representing the yield of the i fruit in the year t; the expression ln(Decare) reflects the natural logarithm value corresponding to the cultivated area of the i fruit in the same year; and the expression ln(Tonit) represents the natural logarithm of the total production amount obtained from the i fruit in that year. Here, αi is a constant effect specific to each fruit, and this effect represents heterogeneity that is not possible to observe but differs, as it is a feature that does not change over time. On the other hand, εit is considered a specific error term and refers to random components that may affect the accuracy of the model. In order to increase the reliability and accuracy of the results obtained during the analysis process, standard errors were clustered specifically for each fruit group and examinations were carried out accordingly. This method aims to guarantee the robustness of the analysis results. In order to ensure the robustness of the findings, standard errors were clustered at the fruit level.

Equations 1, 2 and 3 are estimated as separate reduced-form regressions, each describing the response of a different observable outcome (yield per decare, total tonnage and planted area) to the same set of climatic forcing variables, while controlling for fruit-specific unobserved heterogeneity. The three equations are not solved as a structural system; they are intended to provide a complementary, descriptive decomposition of the channels through which national-level climatic variation is associated with the aggregate fruit production outcome reported in official statistics.

$$ln(Yield) = \beta 0 + \beta 1 \cdot Temperaturekit + \beta 2 \cdot Temperaturekit2 + \beta 3 \cdot ln(Precipitation,it) + \beta 4 \cdot [ln(Precipitation,it)]2 + \alpha i + \varepsilon it \quad (1)$$

$$ln(Tonit) = \beta 0 + \beta 1 \cdot Temperaturekit + \beta 2 \cdot Temperaturekit2 + \beta 3 \cdot ln(Precipitation,it) + \beta 4 \cdot [ln(Precipitation,it)]2 + \alpha i + \varepsilon it \quad (2)$$

$$ln(Decare) = \beta 0 + \beta 1 \cdot Temperaturekit + \beta 2 \cdot Temperaturekit2 + \beta 3 \cdot ln(Precipitation,it) + \beta 4 \cdot [ln(Precipitation,it)]2 + \alpha i + \varepsilon it \quad (3)$$

Quantifying these channels jointly within a fully structural multi-equation model lies beyond the scope of the present paper and is left for future work. In addition, to investigate the heterogeneity of climate effects between fruits, Ordinary Least Squares (OLS) regressions were estimated separately for each of the 63 fruits. This approach allows the climate coefficients to be different for each fruit and includes a linear time trend (Year t) to control technological advances over the period.

The linear time-trend coefficient is interpreted as a reduced-form summary of the combined influence of slowly-evolving, time-correlated factors —such as the diffusion of modern cultivation techniques, the spread of irrigation infrastructure, varietal improvement and changing demand conditions— and is not meant, on its own, to identify a causal effect of "technological progress" in a structural sense.

The fruit-specific OLS model is as given in equation 4 (Monti and Venturi, 2007):

$$ln(Yieldit) = \delta 0 + \delta 1 \cdot Temperaturekit + \delta 2 \cdot Temperaturekit^2 + \delta 3 \cdot ln(Precipitation,it) + \delta 4 \cdot [ln(Precipitation,it)^2] + \delta 5 \cdot Year + uit \quad (4)$$

Here, Yılt is the time trend variable and δ coefficients are estimated separately for each i fruit.

Multiple-testing considerations. Because the fruit-specific OLS regressions are estimated for 63 fruit species, the conventional 5% and 10% significance levels are interpreted with caution: results that are significant at the 1% level (P<0.01) are treated as the most informative, while results that are only marginally significant are discussed as suggestive rather than conclusive. This conservative reading of the species-level coefficients is consistent with standard recommendations for inference in settings with a large number of simultaneous tests.

3. Results and Discussion

In this section, the effects of climate variables on fruit productivity in Türkiye were examined using the Two-Way Fixed Effects panel data model. The main purpose of the research is to reveal the net effect on productivity (Model 1) and to analyse the mechanisms through which this effect occurs. These mechanisms are addressed under two main categories: (i) biological/physiological production process (Model 2: ln(Ton)) and (ii) behavioral/economic changes in cultivation area (Model 3: ln(Dekar)). The section evaluates and interprets the estimation results obtained from the econometric models described in detail. The main findings of the Fixed Effects panel regression (Equation 1-3) are presented in Table 2.

Table 2. Fixed effects (FE) panel regression results (Equation 1)

Variable	(1) ln(Yield)	(2) ln(Tonnes)	(3) ln(Decare)
Temperature	13.372 (-6.13)	32.639 (-6.64)	17.989 (-2.29)
Temperature^2	-0.545 (-6.07)	-1.330 (-6.62)	-0.734 (-2.28)
Precipitation	-0.032 (-3.71)	-0.071 (-4.59)	-0.035 (-1.72)
Precipitation^2	0.00003 (-3.88)	0.00006 (-4.79)	0.00003 (-1.77)
Model Statistics			
Number of Observations (N)	1.254	1.254	1.254
Number of Groups (Fruit)	63	63	63
R-squared (within)	0.1947	0.2946	0.069
Fruit Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes

3.1. Decomposition of Climate Impacts: Production and Area Channels

The estimation results reveal that the temperature and precipitation values that change depending on climate change in Türkiye affect fruit productivity in Türkiye in a statistically significant and non-linear way through both channels.

Looking at Table 2, the first column of the table deals with the net effect and yield dimension, and the first column shows that climate variables have a strong and significant effect on crop productivity at the level of 1%. The findings confirm that climate plays a decisive role in agricultural productivity.

Column 2 of the table examines the production status through the biological channel and reveals the direct effects of the climate on the total production amount, that is, the yield. This model presents the strongest statistical outputs in the analysis. Findings based on large

coefficients such as 32.639 and high t-statistics such as t=6.64 for the temperature variable reveal that climate effects are dominant through biological and physiological mechanisms. It is especially prominent that extreme temperatures and insufficient precipitation have a direct negative effect on the physiological development of plants and fruit set.

In the third column of the table, the selection of planting areas through the behavioral channel is evaluated, and the effects on farmer decisions are discussed. The results of the study show that this channel is statistically significant. Temperature variables affect farmers' planting area decisions at the level of 5% ($P<0.05$) and precipitation variables at the level of 10% ($P<0.10$). This indicates that farmers do not take a passive approach to climate shocks, but rather adapt their choice of planting area and crop to be planted to climate conditions. This adaptation process also reflects risk avoidance efforts.

Although the effect of precipitation and temperature is statistically significant, there is an asymmetry in terms of size. The direct biological effects of climate variables on yield (Model 2) are stronger than farmers' efforts to regulate planting area decisions as a form of behavioural adaptation (Model 3). The total effect on net yield is explained by the combined effect of these two channels.

3.2. Nonlinear Thresholds and Milestone Analysis

The fact that quadratic terms, i.e. Temperature^2 and Precipitation^2 variables, are found to be significant in all models clearly reveals the non-linear relationships between the variables and allows the determination of critical thresholds, in other words, turning points in climatic processes. While these results reflect the complexity of the data analysed, they also make it possible to calculate possible sensitivities within the climate system.

3.2.1. Effect of temperature (inverted U-shape)

One of the issues that has been discussed in the agricultural economics literature for many years is the effect of temperature on agricultural productivity. Research and models reveal that the relationship between temperature and efficiency generally has an "inverted U-shaped" structure. This shows that temperature is a factor that increases efficiency up to a certain level, but after this threshold is exceeded, there is a sharp decrease in efficiency. Temperature is one of the main determinants of agricultural activities. Processes such as plant growth, soil fertility and the water cycle are directly affected by temperature changes. However, the fact that this effect is not linear indicates that the temperature-efficiency relationship has a more complex structure. Within a certain temperature range, the photosynthesis capacity of plants increases and growth accelerates. However, when the temperature rises above this range, it causes stress in plants, reducing their photosynthetic capacity and adversely affecting growth (Schlenker and Roberts, 2009; Bello and Maman, 2015).

- Optimal Temperature (Yield): 12.27 °C
- Optimal Temperature (Production): 12.27 °C
- Optimal Temperature (Area): 12.25 °C

The analysis reveals that the optimal temperature threshold for agricultural productivity is quite evident. The following findings stand out in the analyses made especially in terms of fruit farming:

These data indicate that the temperature threshold at which agricultural activities are optimised is around 12.3 °C in terms of both biological (yield on tonnage basis), behavioural (responses on planted area basis) and net results. This finding exhibits a remarkable consistency in the literature.

These results are quite significant in terms of fruit farming in Türkiye. According to descriptive statistics, the average temperature in Türkiye was determined as 11.92 °C. This shows that Türkiye's fruit agriculture is already operating at the limit of the optimal thermal threshold. However, it is predicted that further increases in temperatures may have an increasingly negative impact on agricultural productivity.

It should be emphasised that the value of approximately 12.3 °C reported above is a panel-level, aggregate optimum that summarises the average response of the 63 fruit species considered to the nationwide annual mean temperature. It is, by construction, not a biological optimum for any single species and should not be interpreted as such; rather, it characterises the macro-level, country-wide association that this paper sets out to reveal. Species-specific biological optima, which would require growing-season indicators and region-of-cultivation climate data, are clearly of complementary interest and are signalled here as a fruitful avenue for future, more narrowly-focused studies.

3.2.2. Effect of precipitation (U-shape)

In terms of agricultural production, precipitation is one of the most critical environmental factors. However, the effect of precipitation, contrary to popular belief, does not increase and decrease linearly. Research shows that there is a "U-shaped" relationship between the amount of precipitation and agricultural productivity. This reveals that both very little precipitation and moderate precipitation have negative effects on productivity, but precipitation has a positive effect after a certain threshold.

Research has revealed that the effect of precipitation on agricultural productivity depends on certain thresholds. Analyses conducted in the context of Türkiye have determined the minimum impact threshold values as follows:

- Minimum Impact Threshold for Yield: 615 mm
- Minimum Impact Threshold for Production: 623 mm
- Minimum Impact Threshold for Area: 625 mm

These threshold values appear to be quite consistent across the three different models. This shows that the effect of precipitation has a structure that is also supported in the scientific literature (Bello and Maman, 2015; Babyenda et al., 2023). The U-shaped effect of precipitation can be explained by two important negative externalities, especially those brought about by moderate

precipitation regimes: Disease Vectors and Leaf Wetness Duration (LWD); moderate precipitation regimes usually mean high relative humidity and prolonged leaf wetness. This creates ideal conditions for the development of fungal and bacterial pathogens. For example, pathogens such as Botrytis cinerea can cause outbreaks in conditions where relative humidity above 90% lasts for hours (Carisse and McNealis., 2019). Increasing the amount of precipitation from 500 mm to 600 mm may increase the risk of such diseases rather than benefiting the plant.

Continuous precipitation regimes are associated with high cloudiness and low solar radiation. This adversely affects the photosynthesis process, which is critical for fruit development. The temporal distribution of precipitation is as important as the total amount; continuous indoor weather conditions can limit the growth and development of plants. In light of these findings, it is seen that the riskiest scenario for fruit farming in Türkiye is not only drought, but also "moderate-humid" regimes that do not fully meet the need for irrigation but maximize the risks of disease and low sunshine.

3.3. Impact of Global Climate Change on Fruit Production

The "average" climate effects (inverse-U for temperature, U-shape for precipitation) presented in Equations (1-3) and Table 2 do not apply to all 63 fruits in the panel. Individual time series OLS regressions based on Equation (4) reveal a statistically and agronomically significant, profound heterogeneity among fruit species.

Our analysis shows that the "average" climate effect is largely due to 14 "sensitive" fruit species. The responses of these sensitive fruits were examined by classifying them below according to which variable they are sensitive to ($P \leq 0.10$).

3.3.1. Fruits positively affected by temperature increase due to global climate change

First, fruits that show temperature sensitivity are examined in Table 3. Five fruits stand out in this group. The findings indicate that the effect is species-specific. The citrus group (Orange, Tangerine) shows a strong and expected response to temperature (5% significance). This confirms how dependent citrus agriculture is on specific thermal thresholds for flowering and fruit set (Timmer and Gottwald, 2000). Interestingly, Blueberries and Carobs show a positive relationship with temperature, suggesting that warming may have increased agricultural suitability for these specific fruits.

Analyses of the responses of fruit species to environmental factors provide important findings in understanding the level of adaptation of different species to climatic conditions and the effects of these conditions on fruit development. It has been statistically demonstrated that varieties such as oranges (Washington, Yafa) and mandarins (Satsuma) are sensitive to low temperatures and that this can have negative consequences. In contrast, blueberries were observed to respond positively to high temperature values and their development was supported under these conditions. It has been determined that the amount of precipitation has negative effects on some fruits, and the increase in precipitation has statistically significant negative results, especially for blueberries. In addition, the fact that the time trend values are generally positive and significant indicates that fruit species have shown a positive development over time and that the effects of climate change on these species have generally followed a positive course. When the R^2 values are examined in terms of the explanatory power of the model, a very high value of 0.971 was obtained, especially for blueberries, which reveals that the model explains the data extremely well. For other fruit species, R^2 values are at lower levels but are acceptable. These findings provide valuable information for assessing the adaptation processes of fruit species to environmental conditions and the potential impacts of these processes on agricultural production. From a physiological standpoint, the negative temperature sensitivity of citrus species such as oranges (Washington, Jaffa) and mandarins (Satsuma) is consistent with well-established floral biology: citrus trees require a relatively narrow chilling period for flower induction, and rising annual mean temperatures can disrupt this vernalisation requirement, reducing flowering synchrony and fruit set (Iglesias and Garrote, 2015). Conversely, blueberries' positive response to temperature reflects their adaptation to cooler temperate climates; moderate warming may extend their effective growing season in higher-altitude Turkish production zones (e.g., the Eastern Black Sea region), increasing cumulative growing-degree days and, consequently, yield per decare. The negative response of blueberries to precipitation corroborates agronomic observations that this crop is highly susceptible to root asphyxiation under waterlogged conditions, requiring well-drained, acidic soils to achieve optimal productivity (Yuan et al., 2024).

These species-level physiological mechanisms highlight that broad-scale climate signals interact with crop-specific biology in ways that cannot be inferred from aggregate statistics alone, underscoring the value of the heterogeneous, species-disaggregated approach adopted in the present study.

Table 3. Fruits significantly affected by temperature variables

Fruit Name	Temperature	Temperature^2	ln(Precipitation)	[ln(Precipitation)]^2	Time Trend (Year)	R^2
Orange (Washington)	-3.24** (0.015)	0.13** (0.015)	22.95 (0.366)	-1.70 (0.381)	0.012** (0.029)	0.564
Orange (Jaffa)	-2.21** (0.023)	0.09** (0.025)	0.56 (0.976)	-0.01 (0.996)	0.016*** (0.001)	0.645
Mandarin (Satsuma)	-2.64** (0.035)	0.11** (0.035)	10.43 (0.667)	-0.77 (0.679)	0.027*** (0.000)	0.763
Blueberry	36.00* (0.072)	-0.08 (0.238)	-0.76*** (0.003)	6.25 (0.171)	0.069*** (0.000)	0.971
Carob	3.19** (0.047)	-0.03 (0.733)	-0.0024	1.74 (0.325)	0.007* (0.056)	0.602

P-values are shown in parentheses. *** P<0.01, ** P<0.05, * P<0.10.

Table 4. Fruits significantly affected by precipitation variables

Fruit Name	Temperature	Temperature^2	ln(Precipitation)	[ln(Precipitation)]^2	Time Trend (Year)	R^2
Avocado	3.09 (0.133)	-0.12 (0.139)	-88.52** (0.046)	6.75** (0.047)	0.030*** (0.002)	0.778
Fig (Fresh)	-0.39 (0.705)	0.01 (0.711)	44.07* (0.053)	-0.1848	0.014*** (0.005)	0.646
Apple (Starking)	1.89 (0.131)	-0.08 (0.136)	-55.52** (0.040)	4.23** (0.041)	-0.006 (0.222)	0.356
Other Apples	1.52 (0.305)	-0.06 (0.309)	-4.65108	4.24* (0.084)	0.011* (0.089)	0.494
Nectarine	0.27 (0.824)	-0.01 (0.810)	-4.302	3.29* (0.101)	0.013** (0.018)	0.494
Plum	0.54 (0.418)	-0.02 (0.406)	-2.21494	1.86* (0.092)	0.015*** (0.000)	0.813
Blueberry	36.00* (0.072)	-0.08 (0.238)	-0.76*** (0.003)	6.25 (0.171)	0.069*** (0.000)	0.971
Almond	2.30 (0.137)	-0.10 (0.130)	-4.51776	4.45* (0.078)	-0.003 (0.663)	0.269
Carob	3.19** (0.047)	-0.03 (0.733)	-0.0024	1.74 (0.325)	0.007* (0.056)	0.602
Pomegranate	1.07 (0.186)	-0.04 (0.196)	-39.82** (0.026)	3.03** (0.026)	0.029*** (0.000)	0.933

P-values are shown in parentheses. *** P<0.01, ** P<0.05, * P<0.10.

3.3.2. Fruits significantly affected by the precipitation variable due to global climate change

The findings presented in Table 4 reveal the effect of precipitation variables on different fruit species. Avocado, Apple, Nectarine, Plum, Almond and Pomegranate exhibit a U-shaped relationship with the effect of precipitation, indicating that moderate precipitation may be a greater problem for these fruits than drought. This supports the negative effects of increased leaf wetness duration and associated pathogenic risks on these fruits. On the other hand, the Fig (Fresh) fruit shows an inverse-U-shaped relationship with precipitation, revealing that precipitation is beneficial up to a certain point, but excessive precipitation reduces yield due to reasons such as fruit cracking or rotting. Blueberries, on the other hand, exhibit a strong negative linear relationship with precipitation, emphasising that excessive precipitation is harmful at all levels and that they need well-drained soils. These findings clearly demonstrate the diversity of responses of different fruit species to precipitation and their sensitivity to environmental conditions.

The effect of the precipitation variable is statistically significant for some fruits. For example, fruits such as avocado, fig (fresh), pomegranate and blueberries show the positive effect of the precipitation variable. These fruits appear to be highly sensitive to precipitation. While avocado shows the negative effect of precipitation,

temperature and time trend show a positive effect. While blueberries show the highest positive effect of the temperature variable, the effect of precipitation seems to be less pronounced. While pomegranate shows the negative effect of precipitation, the effect of temperature is more modest. Table 4 reveals the sensitivity of certain fruit species to precipitation and the effect of temperature and time trends. Fruits such as avocado, pomegranate and blueberries, in particular, are positively affected by the precipitation variable, while they react differently to different temperature levels. The agronomic underpinnings of these precipitation responses merit deeper consideration. The U-shaped relationship between precipitation and yield for avocado, almond, plum, nectarine and pomegranate can be explained by the dual role of moisture in horticultural systems. At the lower end of the precipitation distribution, soil moisture deficits during critical phenological stages — flowering, fruit set and cell expansion — constrain yield directly. At intermediate precipitation levels, however, elevated atmospheric humidity and prolonged leaf wetness duration create favourable conditions for fungal pathogens (notably Botrytis cinerea and Alternaria spp.), reducing marketable yield through post-infection losses (Carisse and McNealis, 2019).

The inverse-U relationship observed for fresh fig is physiologically consistent with the known sensitivity of this species to fruit cracking caused by sudden heavy rains following a dry spell, which ruptures the epidermis and exposes fruit flesh to secondary infections. Pomegranate's negative response to precipitation (both linear and quadratic terms significant at the 5% level) aligns with recent findings by Yang et al. (2024), who reported that this species is prone to fruit-splitting under high-rainfall conditions and thrives in semi-arid climates with supplemental irrigation. These mechanistic interpretations reinforce the policy relevance of the results: targeted irrigation management — maintaining optimal soil moisture while minimising aerial humidity — emerges as the most effective agronomic lever for sustaining yields under changing precipitation regimes in Türkiye.

In addition, the "Time Trend" variable shown in Table 5 has a significant effect on 12 fruits representing technological progress or long-term structural changes. The inclusion of 12 of the 14 sensitive fruits in this group reveals that the yield dynamics of these fruits are largely sensitive to technological developments and structural changes over time.

Avocado, blueberries, pomegranate and citrus fruits (oranges, mandarins), which are high-value products, exhibit strong positive trend coefficients, indicating that new varieties, modern agricultural techniques and increasing demand in these sectors have a significant impact on productivity.

The most striking finding in this group is the walnut. Walnut shows a strong and negative time trend (coefficient=-0.026) at 1% significance level. This is a critical finding that reveals that, contrary to the assumption of technological progress, walnut productivity in Türkiye has decreased statistically over time, possibly due to reasons such as ageing tree population, systemic diseases or soil fatigue (Table 5).

Looking at Table 5, high-value fruits such as avocado, blueberries and pomegranate attract attention with their positive time trends. This shows that the productivity of these fruits has increased with modern agricultural techniques and increasing demand. Walnut shows a negative time trend (coefficient=-0.026). This indicates that walnut productivity in Türkiye has decreased over time and this may be due to the aging tree population or other environmental factors.

Other noteworthy findings in the table are that avocado shows high productivity with positive temperature and time trend coefficients (R^2=0.778). Fig has a positive time trend, but the temperature effect is uncertain (R^2=0.646). Orange (Washington and Jaffa), both species have positive time trends, but temperature coefficients are negative and may have negative effects on productivity (R^2=0.564 and R^2=0.645). Mandarin (Satsuma) shows an increase in productivity with a positive time trend and a high R^2 value (0.763). Other Apples and Nectarines have positive time trends but lower R^2 values (0.494), indicating a less pronounced increase in productivity. Plum shows a remarkable increase in yield with a positive time trend and R^2=0.813. Blueberries show a strong yield increase (R^2=0.971) with a very high positive time trend (0.069***). Carob (Harnup) has an uncertain temperature effect, but a positive time trend (R^2=0.602). Pomegranate shows an increase in yield with a strong positive time trend (0.029***) and a high R^2 value (0.933).

3.3.3. Fruits that do not Respond Statistically to Climate

Finally, 49 (78%) of the 63 fruit species included in the analysis did not show a statistically significant response to either climate variables or time trend at the 10% level, as listed in Table 6 (Table 6).

The effects of climate change on agricultural production should not be evaluated only with short-term observations, but should be addressed with long-term and multifaceted analyses. The fact that 49 of the 63 fruit species examined did not show a statistically significant response to climate variables or time trends should not be interpreted as meaning that these species are not affected by climate change.

The inclusion of traditional and relatively resistant species such as olives, hazelnuts, grapes and apricots in this group reveals the impact of agricultural practices. Methods such as intensive irrigation, disease management and measures taken against frost contribute to the fact that these species appear to be more resistant. However, this does not mean that these species are completely immune to climate change. On the contrary, it is of great importance to analyse in detail the

mechanisms that ensure the resilience of these species and to develop sustainable agricultural practices in this context. Improving existing practices and implementing innovative strategies is a critical requirement to minimise the negative effects of climate change on agricultural production (Table 6).

Table 5. Fruits significantly affected by time trend

Fruit Name	Temperature	Temperature^2	ln(Precipitation)	[ln(Precipitation)]^2	TT (Year)	R^2
Avocado	3.09 (0.133)	-0.12 (0.139)	-88.52** (0.046)	6.75** (0.047)	0.030*** (0.002)	0.778
Fig (Fresh	-0.39 (0.705)	0.01 (0.711)	44.07* (0.053)	-0.1848	0.014*** (0.005)	0.646
Orange (Washington	-3.24** (0.015)	0.13** (0.015)	22.95 (0.366)	-1.70 (0.381)	0.012** (0.029)	0.564
Orange (Jaffa	-2.21** (0.023)	0.09** (0.025)	0.56 (0.976)	-0.01 (0.996)	0.016*** (0.001)	0.645
Tangerine (Satsuma	-2.64** (0.035)	0.11** (0.035)	10.43 (0.667)	-0.77 (0.679)	0.027*** (0.000)	0.763
Other Apples	1.52 (0.305)	-0.06 (0.309)	-4.65108	4.24* (0.084)	0.011* (0.089)	0.494
Nectarine	0.27 (0.824)	-0.01 (0.810)	-4.302	3.29* (0.101)	0.013** (0.018)	0.494
Plum	0.54 (0.418)	-0.02 (0.406)	-2.21494	1.86* (0.092)	0.015*** (0.000)	0.813
Blueberry	36.00* (0.072)	-0.08 (0.238)	-0.76*** (0.003)	6.25 (0.171)	0.069*** (0.000)	0.971
Walnut	0.75 (0.603)	-0.03 (0.602)	-41.72 (0.177)	3.19 (0.178)	-0.026*** (0.000)	0.725
Carob	3.19** (0.047)	-0.03 (0.733)	-0.0024	1.74 (0.325)	0.007* (0.056)	0.602
Pomegranate	1.07 (0.186)	-0.04 (0.196)	-39.82** (0.026)	3.03** (0.026)	0.029*** (0.000)	0.933

P-values are shown in parentheses. *** P<0.01, ** P<0.05, * P<0.10. TT= time trend

Table 6. Fruits with No Significant Climate Impact

Product Name				
Table Grapes, Seeded	Apricots	Persimmons	Mulberries	Tangerines / Mandarins (Clementine)
Table Grapes, Seedless	Wild Apricots (Zerdali)	Table Olives	Chestnuts	Tangerines / Mandarins (King)
Wine Grapes	Sweet Cherries	Olives for Oil Production	Hazelnuts	Tangerines / Mandarins (Other)
Raisins (Dried Grapes), Seeded	Sour Cherries	Tea Leaves	Pistachios	Kiwi (Kiwifruit)
Raisins (Dried Grapes), Seedless	Peaches	Dried Pepper, Unprocessed	Medlar	Raspberries
Bananas, Plantains and Similar	Loquat (Maltese Plum)	Anise, Unprocessed	Apples (Golden Delicious)	Strawberries
Grapefruit (Pomelo)	Cornelian Cherry	Cumin, Unprocessed	Apples (Amasya)	Thyme / Oregano, Unprocessed
Lemons and Limes	Oleaster (Russian Olive)	Fennel, Unprocessed	Apples (Granny Smith)	Sorghum (Broomcorn), Unprocessed
Other Oranges	Jujube	Coriander, Unprocessed	Pears	Capers, Unprocessed
Bitter Orange (Sour Orange)	Black Cumin Seeds (Nigella Sativa)	Blackberries	Quince	

4. Conclusion

Increasing temperatures due to global climate change pose serious risks to agricultural production. In countries such as Türkiye, which has an important role in agriculture, it may become inevitable to experience declines in agricultural productivity if optimal temperature thresholds are exceeded. These risks become even more evident, especially in temperature-sensitive sectors such as fruit farming. In this context, the measures to be taken to adapt to climate change are of great importance. More resilient plant species need to be developed, irrigation technologies improved and agricultural policies reorganised to take into account climate change risks.

The study analysed the effects of global climate change (temperature and precipitation) on fruit productivity with the Fixed Effects Panel Model for 63 fruit species in Türkiye with data between 2004-2024. The analysis showed that climate affects agricultural productivity in a statistically significant and non-linear way through both yield per decare (tonnes) and behavioural cropland selection (decares) channels.

In the study, in which the relationships between climate variables and yield were modelled with quadratic terms, it was determined that the increase in temperature increased productivity up to a certain point, but a sharp decrease was experienced when this threshold was exceeded. The optimal temperature threshold for fruit farming in Türkiye was determined to be approximately 12.3 °C. According to descriptive statistics, the average temperature in Türkiye (11.92 °C) is very close to this threshold, so it is predicted that future temperature increases will have an increasingly negative impact on productivity.

It has been found that very little precipitation and also moderate precipitation have negative effects on productivity, but have a positive effect after a certain threshold. This threshold is around 615-625 mm on average. It has been emphasised that moderate precipitation regimes are risky, especially because they maximise the risks of disease and low sunshine.

Of the 63 species analysed, 14 showed a significant response to climate variables (Delicate Fruits), 5 fruit species (Orange Washington, Orange Jaffa, Mandarin Satsuma, Blueberry and Carob) showed a significant change due to temperature increase. 10 fruit species (Avocado, Fig (Fresh), Apple (Starking), Other Apples, Nectarine, Plum, Blueberry, Almond, Carob, Pomegranate) were found to be significantly affected by precipitation. It was stated that 49 fruit species (78%) did not show a statistically significant response to climate variables or time trends (e.g. olives, hazelnuts, grapes and apricots), possibly due to resilience achieved through traditional agricultural practices such as intensive irrigation and disease management.

High-value products (Avocado, Blueberry, Pomegranate, Citrus) have shown strong positive time trends, demonstrating that technological advances and modern agricultural techniques in these sectors have significantly increased productivity. However, walnut showed a negative time trend due to reasons such as aging tree population or systemic diseases.

This study clearly demonstrates the need for more conscious and sustainable use of agricultural land and more proactive measures to adapt to climate change. Several concrete policy implications follow from these findings. First, given that the national average temperature of 11.92 °C is already at the estimated aggregate optimum threshold of 12.3 °C, the Turkish Ministry of Agriculture and Forestry should accelerate the integration of climate projections into national fruit-sector planning, prioritising the development and dissemination of heat-tolerant citrus and stone-fruit varieties through the network of provincial agricultural research institutes. Second, irrigation policy should be rationalised on a species-specific basis: for avocado, pomegranate and apple, drip-irrigation systems that maintain root-zone moisture within the optimal range while minimising foliar wetness would mitigate the U-shaped precipitation risks identified in this study. Third, for walnut — which exhibits a statistically significant downward productivity trend independent of climate — a dedicated national programme targeting the rejuvenation of ageing orchards and the management of soil-borne diseases (Phytophthora spp., Armillaria spp.) appears warranted. Fourth, the positive adaptation responses observed for high-value crops such as avocado, pomegranate and blueberry suggest that selective expansion of these species in climatically suitable micro-regions of southern and western Türkiye represents a viable strategy for maintaining agricultural income under warming scenarios, and merits dedicated support through targeted rural development funds and export-promotion programmes. These recommendations, grounded in the empirical findings of the present study, are intended to contribute to evidence-based climate adaptation planning for Türkiye's fruit sector.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	M.Ö.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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