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The impact of climate variability on the Mediterranean agriculture: The case of tomatoes and cereals

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Dedication

This thesis is dedicated to **my parents**, whose enduring love, support, and sacrifices have been the cornerstone of all my achievements. Your belief in me has been a constant source of strength and motivation, and words cannot fully express the depth of my gratitude for your endless encouragement.

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Abstract

The Mediterranean Sea Basin is recognized as a climate hotspot, primarily due to its vulnerability to the impacts of climate change. This region experiences warming trends compared to the global average, leading to increased evapotranspiration rates and significant alterations in agricultural water needs. Climate models project substantial shifts in precipitation patterns, including changes in seasonality and an increased frequency of extreme events such as droughts and heavy rainfall. These factors exacerbate existing challenges related to water scarcity, posing critical threats to agriculture, ecosystems, and socio-economic stability in the Mediterranean Basin. This study investigates the effects of climate change and rainfall variability on the crop water use of tomatoes, maize, and wheat in Mediterranean countries, with a particular focus on Italy. Drawing from previous studies results and regional meteorological data, the study uses a combination of QGIS spatial analysis and Python programming to analyze past climate records from 1990 to 2019, agricultural land use patterns, soil characteristics, and topography. The integrated approach employs the AquaCropEarth@lternatives (ACEA) model, a global process-based crop model, to simulate daily crop growth and water balance. This model distinguishes between green water from precipitation and blue water from irrigation, evaluating both rainfed and irrigated systems. The results highlight significant impacts of altered precipitation regimes on agricultural water use, emphasizing the urgent need for adaptive water management strategies. Key findings indicate varying trends in crop water use (CWU) for tomatoes, maize, and wheat across the Mediterranean region, with notable increases and decreases influenced by climate variability. The study concludes by advocating for efficient irrigation practices, drought-resistant crop varieties, and advanced irrigation scheduling to enhance agricultural resilience and ensure food security amidst climate uncertainties in the Mediterranean Basin.

Keywords: Climate change impacts, Mediterranean climate hotspot, crop water use, rainfall variability, Italy, QGIS spatial analysis, Python programming, adaptive water management, food security, agricultural resilience

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Introduction

Climate variability, encompassing extreme temperatures, changes in precipitation regimes, extreme weather events, and increased atmospheric CO_2 concentrations, poses a significant challenge to agriculture globally. The agricultural sector, directly dependent on weather and climate conditions, is particularly vulnerable to these changes. Studies indicate that climate change can substantially affect crop productivity, growth rates, photosynthesis, and moisture availability, thus threatening food security (Mahato, 2014; Aryal et al., 2020). For the Mediterranean region, characterized by a mix of arid, semi-arid, and temperate climates, even minor global climate modifications can lead to significant changes (Giorgi and Lionello, 2008). This region is projected to experience higher temperatures and decreased precipitation, increasing the pressure on water resources already scarce in several areas.

Crop Water Use (CWU), quantified through the water footprint (WF) methodology, provides critical insights into the freshwater appropriation in agricultural systems. CWU encompasses both green water from natural precipitation and blue water from irrigation or capillary rise, offering a comprehensive view of water consumption across different crop types and geographic regions (Mekonnen and Hoekstra, 2011). The assessment of CWU involves sophisticated models like AquaCropEarth@lternatives (ACEA), which integrates AquaCrop-OSPy to simulate daily crop growth and soil water balance at high spatial resolutions (Mialyk et al., 2017). This approach enables the distinction between green and blue water fluxes in the soil, facilitating a detailed analysis of consumptive water footprints. By considering historical agricultural developments and scaling harvested areas based on comprehensive datasets, ACEA improves the accuracy of CWU estimations over extended periods, offering valuable data for sustainable water management and policy formulation (Mialyk et al., 2017). The water footprint (WF) of crops, defined as the volume of water consumed per unit of harvested crop, encompasses both green water from precipitation and blue water from irrigation or capillary rise (Mekonnen & Hoekstra, 2011). Understanding WF patterns is essential for sustainable water management, especially in regions facing water scarcity like the Mediterranean. Global assessments have shown that crop production consumes significant volumes of both green and blue water, with global estimates indicating around 5.8 trillion m^3 of green and 0.9 trillion m^3 of blue water annually for crop production, accounting for 87% of humanity's water consumption (Mekonnen and Hoekstra, 2011).

The Mediterranean region, a vital agricultural hub, is expected to be heavily impacted by climate change due to its geographical location. The region is identified as a "hot spot" in future climate change projections, with anticipated larger warming than the global average and significant reductions in precipitation (Giorgi, 2006; Lionello et al., 2014). These changes are likely to affect vegetation water availability, crop yields, and water productivity, with increased temperatures and decreased rainfall leading to greater water scarcity (Pereira, 2011). Increased atmospheric CO_2 concentrations may initially enhance crop growth; however, this benefit is often offset by the accompanying stress of higher temperatures and reduced water availability, resulting in lower yields overall (Ainsworth & Long, 2005; Zwart et al., 2010; Milano et al., 2012).

Tomatoes represent 13.5% of the world's vegetable production (FAO, 2023). In Italy, around 97610 ha are devoted to tomato cultivation, which yielded 62.86 ton/ha of tomatoes in 2022 (FAO, 2023). Southern Italy is part of the Mediterranean region, which has a semi-arid climate. It is expected that climate change will negatively affect vegetation and water availability in the Mediterranean (Pereira, 2011), which could create problems for tomato production. Maize represents approximately 26.1% of the world's grain production (FAO, 2023). In Italy, maize cultivation covers approximately 1,211,000 hectares, with a yield of 8.5 tons per hectare in 2022 (FAO, 2023). Wheat accounts for approximately 20.5% of the world's grain production (FAO, 2023). In Italy, wheat cultivation spans about 1,803,000 hectares, yielding 3.74 tons per hectare in 2022 (FAO, 2023). Maize and wheat cultivation in the Mediterranean region, particularly in semi-arid climates like Southern Italy, are also susceptible to the impacts of climate change. Climate projections indicate that increasing temperatures and changes in precipitation patterns could adversely affect crop yields and water availability (Giorgi and Lionello, 2008).

1-1- Goals of this study

This study aims to evaluate the impact of climate variability on Mediterranean agriculture, specifically examining the crop water use variation of tomatoes, maize, and wheat over the period 1990 to 2019. The study will utilize advanced models to simulate the water footprints and crop yields of these crops in the Mediterranean basin, with a particular emphasis on Italy. By analyzing recorded data obtained from the ACEA based on the AquaCrop model, using Qgis and Python codes, this research seeks to determine whether climate change has had a discernible impact on the water use of these crops in the region.

The goals of this study are:

1. To quantify the total unit water footprint (m^3/ton year) and crop water use (mm/year) of tomatoes, maize, and wheat in the Mediterranean region, particularly Italy, from 1990 to 2019.
2. To assess and compare the impact of climate variability on the water use of these crops.
3. To provide insights into sustainable water management practices that can mitigate the adverse effects of climate change on agriculture in the Mediterranean region.

1-2- Main concepts

1-2-1-Climate variability and its effects on agriculture in the Mediterranean Region

The Mediterranean region occupies a unique transition zone between the mild, rainy climate of Central Europe and the arid climate of North Africa. This geographical position subjects the region to interactions between mid-latitude and tropical climate processes, making it highly sensitive to even minor climatic shifts. Historically, the Mediterranean has experienced significant climate changes over the centuries (Luterbacher et al., 2006), and it is currently identified as a critical "hot spot" in climate change projections. A "hot spot" is defined as a region where the impacts of climate change on the environment or various sectors are particularly pronounced, providing valuable insights into the primary processes driving regional climate change (Giorgi, 2006).

Recent data indicate that the average yearly temperatures in the Mediterranean are now approximately 1.5°C higher than during the pre-industrial period (1880–1899), exceeding the global average increase of +1.1°C. The average annual temperature rise in the region is 0.03°C, which is also above the global trend (Cramer et al., 2019). Projections suggest that this positive trend in air temperature will continue, leading to temperatures that will be above the global average in the future. Alongside rising temperatures, a decrease in precipitation is anticipated. For example, between 2000 and 2050, an annual reduction of 39.1 (±5.1) mm in rainfall and an increase of 1.57 (±0.27)°C in temperatures are expected (Saadi et al., 2015). Summer rainfall is projected to decrease by 10–15% in France, northwestern Spain, and the Balkans, and by 30% in Turkey if global temperatures rise by 2 degrees (Cramer et al., 2019). By the end of the 21st century, the Mediterranean region is predicted to be 20% warmer than the global average, with this rate currently at 36% as of 2020 (MedECC, 2020). Moreover, during summer, the region's excess warming rate could be about 50% higher than the global average. With increasing average temperatures globally, precipitation in the Mediterranean is projected to decrease by 4% (20 mm) (Lionello & Scarascia, 2018).

Studies have shown that climate change has severe impacts on the ecosystems and agricultural production of the Mediterranean basin. For instance, olive cultivation, which holds significant socio-economic importance for the region, is particularly vulnerable. Tanasijevic et al. (2014) predicted that by 2050, rain-fed olive groves will suffer from such severe water stress that production will become nearly impossible. Similarly, Ponti et al. (2014) found that a 1.8°C increase in temperature reduces olive yields, increases olive fly infestation, and subsequently decreases profitability for small olive farms. These small farms play a crucial role in soil and biodiversity conservation and fire risk reduction in the area.

Further research by Fader et al. (2015) examined the extent of climate change's impact on irrigation needs by the 2080s. Crops such as olives, grapes, cotton, and sugar cane, which are grown in the Mediterranean, consume more irrigation water per hectare than average. Countries like Algeria, Libya, Israel, Lebanon, Syria, Morocco, Tunisia, and Spain face the highest risk of water scarcity. Climate change alone is expected to increase gross irrigation needs by 4 to 18%, and these rates could rise to 22–74% when considering population growth. However, advanced irrigation technologies can help save up to 35% of water in the region. Temperature increases also impact the cooling needs of certain crops, affecting the sustainability and efficiency of crops like apples. Funes et al. (2016) predicted that from the mid-21st century, apple varieties will experience delays in blooming dates, ultimately affecting apple production in the region.

Climate change imposes numerous direct and indirect impacts on sustainable agriculture. Direct effects include geographical and seasonal redistribution of climate resources for agriculture and changes in operating costs (heating-cooling, insurance premiums). Indirect costs arise from environmental changes related to climate issues such as water scarcity, biodiversity loss, increased vector-borne diseases, and infrastructure damage. Additionally, climate change is expected to negatively affect agricultural competitiveness due to rising oil and chemical fertilizer prices, disproportionately impacting farmers with limited capital (Bocci & Smanis, 2019).

1-2-2-ACEA model

ACEA is a Python-based tool with a three-stage simulation procedure as illustrated in figure 1-1. In the first stage, ACEA gathers crop and environmental input data for each grid cell within the study area. The spatial resolution of these inputs defines the grid cell size, while the geographical scope of rainfed and irrigated production systems determines the number of cells. Depending on water availability, various rainfed and irrigation configurations can be chosen. Rainfed configurations include fully rainfed (s1) and rainfed with shallow groundwater (s2). Irrigation configurations include surface irrigation (s3), sprinkler irrigation (s4), drip irrigation (s5), and surface irrigation with shallow groundwater (s6). Additionally, crop management can be tailored by selecting field practices (such as mulches, weed control, and bunds) and adjusting irrigation strategies. In the second stage, ACEA executes AquaCrop-OSPy independently within each grid cell, meaning lateral processes like water inflow from neighboring cells are not accounted for. The primary output variables are crop yield and crop water use (CWU) with all outputs. In the third stage, ACEA compiles the raw outputs from each grid cell into global gridded datasets in NetCDF format and then performs optional post-processing steps. These steps include crop yield scaling, water footprint (WF) calculation, statistical analysis, and visualization (Mialyk et al, 2022).

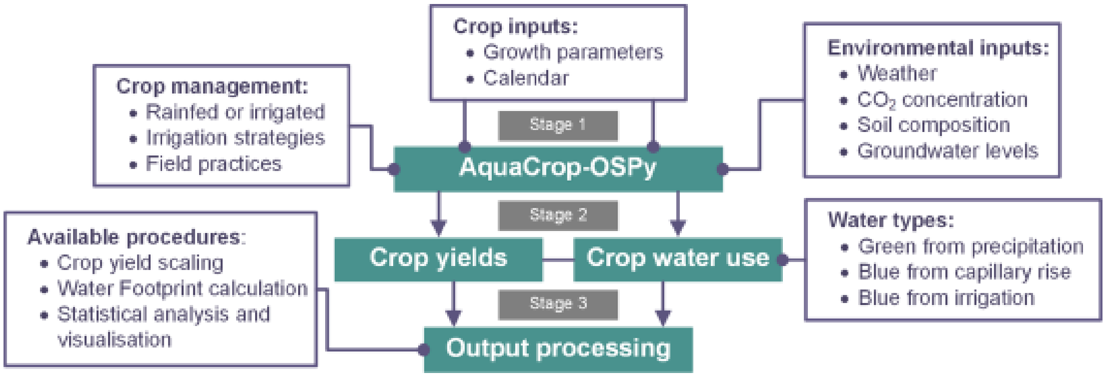


Figure 1-1- ACEA's simulation framework

1-2-3-AquaCrop-OSPy and green–blue water calculation

AquaCrop-OSPy, which is a Python implementation of the FAO's AquaCrop application version 6.1, is used. Data on crop, soil, climate, field, and irrigation management in figure 1-1 are used to simulate daily crop growth and the soil water balance. The water balance includes inputs such as precipitation, irrigation, and capillary rise (CR), and outputs including runoff, evaporation (E), transpiration (T), and deep percolation. Upward and downward fluxes between soil compartments (figure 1-2) are also considered. Crop growth is driven by temperature through growing degree days (GDDs) and is represented by variables such as effective rooting depth and canopy cover. Canopy cover is used to convert potential evapotranspiration (ET0) into transpiration, which influences dry above-ground biomass growth through a CO2-adjusted water productivity factor. At the end of the growing season, the accumulated biomass is converted into dry crop yield via a harvest index. The impacts of thermal and water stresses on crop growth are accounted for; for instance, water stress can cause stomatal closure and limit canopy expansion, thereby reducing transpiration and biomass growth. It should be noted that the nutrient cycle and water salinity are not simulated by AquaCrop-OSPy.

A key contribution to the AquaCrop-OSPy code is the integration of green-blue water accounting, with additional modifications in the ACEA model. Following the framework by Hoekstra (2019), each input flux is classified into one of three water types: green water from precipitation, blue water from CR, or blue water from irrigation (illustrated by the colored boxes in figure 1-2). Upon entry, these water fluxes are assumed to mix uniformly with the soil moisture in either the upper or lower parts of the soil profile. Subsequently, this mixed water is redistributed via gravitational and capillary forces through upward and downward fluxes between soil compartments. The mixed water is then used for evapotranspiration (ET)—evaporation from the upper soil profile and transpiration from all compartments within the effective rooting depth. Consequently, the volumes of the three water types in each soil compartment are in constant flux. This dynamic process implies that the composition of ET varies daily, enabling accurate estimation of crop water use (CWU) for each water type (Mialyk et al, 2022).

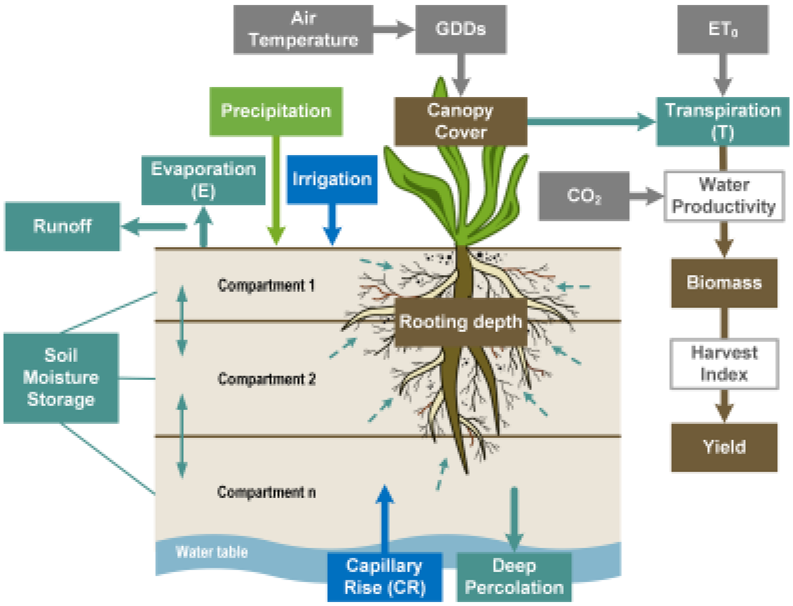


Figure 1-2- AquaCrop simulation scheme

Green, blue, and cyan boxes represent variables related to the soil water balance, brown boxes to crop growth, and gray boxes to climate.

1-2-4- Water footprint calculation

To calculate the water footprint of agricultural products, the unit water footprint (uWF) is a crucial measure that indicates the volume of water required to produce a unit amount of product, expressed in cubic meters per ton (m^3/t) or liters per kilogram (L/kg). This calculation includes both green water (from rainfall) and blue water (from surface and groundwater sources). The uWF can be differentiated into the uWF of production (uWFp) and the uWF of supply (uWFs). The uWFp is determined based on actual crop evapotranspiration and yield, considering annual variations. This measure helps in assessing the water needed for locally produced crops over time.

The uWFs, on the other hand, accounts for domestic supply, which includes both local production and imports. It provides a weighted average of the water footprint of locally produced goods and those imported from other regions. This approach allows for a more comprehensive understanding of water use, as it considers the contributions of different sources to the total supply. By integrating these aspects, the water footprint calculation provides insights into the efficiency of water use in agricultural production and helps identify areas for improving water management practices (Tamea et al, 2021).

The concept of water footprint encompasses the volume of water withdrawn to produce a food crop. The unit Water Footprint is expressed as the water footprint per unit mass of produced goods, denoted dimensionally as a volume over the mass of the product [m^3/ton]. This analysis centers on the partitioning of the Water Footprint into its green and blue components, examining their spatio-temporal variability through 5 × 5 arc-minute resolution global maps, corresponding to approximately 9 km × 9 km pixels at the equator (Tuninetti et al., 2015). In each pixel, the unit Water Footprint is determined as the ratio of water evapotranspiration of crops during their growing period, $ET_{a,\ (i,\ j),\ y}$ [mm/year], to the crop yield in that specific cell, $Y_{(i,\ j),\ y}$ [ton/ha]. This calculation yields the cubic meters of water per ton of product for each cell (i, j) in the global grid at a given year (y), allowing for a comprehensive assessment of water usage efficiency.

$$uWF_{(i,\ j),y} = 10\times\ [m^3/ton]$$

The consideration of green and blue components is integral to this analysis, with green evapotranspiration (ET_g) accounting for the output related to precipitation, and blue evapotranspiration (ET_b) representing the contribution from irrigation. The distinction between these components is crucial in understanding the sources of water consumption in agricultural contexts (Tuninetti et al., 2015).

$$ET_a = ET_b + ET_g$$

ACEA calculates the annual consumptive unit WF (m^3/ ton year) of a crop as the sum of three WF components(Mialyk et al, 2022):

$$WF = WF_g + WF_{bc} + WF_{bi}$$

where WF_g is the green WF, WF_{bc} is the blue WF from CR, and WF_{bi} is the blue WF from irrigation. Each unit WF component is calculated as the crop water use CWU_x (mm/ year) of a water type x (g, bc, or bi) over crop yield Y (ton/ ha year).

To convert from millimeters per year (mm yr^{-1}) into cubic meters per hectare per year (m^3 $ha^{-1}yr^{-1}$), CWU_x is multiplied by 10:

$$WF_x = \frac{CWUx \cdot 10}{Y}$$

To obtain Y , the simulated crop yield Y_s in AquaCrop-OSPy is corrected by two unitless coefficients. The first one is a conversion coefficient from dry to fresh crop yield K_f (0.87 for maize); the second one is a yield scaling factor S, which is introduced to account for external developments not modeled in ACEA:

$$Y = \frac{Ys \cdot S}{Kf}$$

The simulated water availability setups are combined to analyze rainfed and irrigated production systems. In the case of rainfed systems, unit WF_s of a water type x from setups s1 and s2 (the rainfed setups include fully rainfed and rainfed with presence of shallow groundwater) are simply summed as rainfed grid cells always only have one setup. On the other hand, in irrigated systems, the same grid cell can have several irrigated setups (s3 to s6) at once which are the irrigation setups include surface irrigation (s3), sprinkler irrigation (s4), drip irrigation (s5), and surface irrigation with presence of shallow groundwater (s6) . Therefore, irrigated unit WF_s are multiplied by irrigation factor K_i before being summed. The latter reflects a fraction of irrigated area under the respective irrigation method obtained from Jägermeyr et al. (2015):

$$\text{Rainfed } WF_x = WF_{x,s1} + WF_{x,s2}$$

$$\text{Irrigated } WF_x = \sum_{i=s3}^{s6} WF_{x,i} \cdot K_i$$

1-2-5-Crop yield scaling

In recent decades, cereals like maize yields have increased globally due to long-term agricultural developments such as improved irrigation, fertilizers, machinery, chemical control of weeds and insects, and better crop varieties with enhanced resistance to stress. Additionally, short-term factors such as political disruptions, economic conditions, and natural events have caused variability in maize yields. These developments are not explicitly modeled in the ACEA framework due to limitations in input data or the absence of required processes in AquaCrop-OSPy. To account for these factors, yield scaling factors (S) are used to align simulated yields with annual statistics from FAO. S is calculated as the ratio of FAO-reported national crop production (P_{FAO}) to the simulated crop production (P_{ACEA}) within ACEA, ensuring consistency across all grid cells within a country.

$$\mathrm{S} = \frac{P_{FAO}}{\sum Rainfed\ P_{ACEA} + \sum Irrigated\ P_{ACEA}}$$

$$\text{Rainfed } P_{ACEA} = \frac{(Y_{s,s1}+Y_{s,s2})\ .\ A_{rainfed}}{k_f}$$

$$\text{Irrigated } P_{ACEA} = \left(\sum_{i=s3}^{s6} \frac{Y_{s,i}\ .\ K_i}{k_f}\right) \cdot A_{irrigated}$$

The simulated crop yield (Y_s) is calculated for specific water availability setups (rainfed: s1 and s2, irrigated: s3–s6), with historical rainfed and irrigated harvested areas ($A_{rainfed}$ and $A_{irrigated}$) also taken into account. Interannual variability in the scaling factors (S) results in interannual variability in crop yields and, consequently, in unit Water Footprints (WFs). However, the aim is to capture the effects of long-term external conditions while maintaining the modeled climate-related interannual variability. To achieve this, a 3-year moving average of the scaling factors for each country is used (incorporating the previous, current, and next year's factors). This approach preserves the overall trend and variability in historical crop yields while attenuating extreme responses to short-term external developments.

It could be argued that Crop Water Use (CWU) should also be scaled. However, only Y_s is scaled for several reasons. First, improvements in crop varieties (e.g., the angle and size of leaves) can alter the ratio of transpiration (T) to evaporation (E), but these changes have minor effects on CWU since an increase (or decrease) in T is compensated by a decrease (or increase) in E. Both E and T consume green and blue water, so significant changes in green and blue CWUs are not expected. Second, the historical increase in plant density mainly increases maize yields, while CWU values remain relatively similar for the aforementioned reasons. A sensitivity analysis with the model confirms this. Third, the application of nitrogen fertilizer can marginally increase CWU initially, but additional fertilizer does not always lead to a larger CWU. In this study, it is assumed that there is no nutrient stress (i.e., optimal nutrient supply) since AquaCrop-OSPy cannot simulate the nutrient cycle. This may result in an overestimation of CWU in areas without fertilizer use. However, it is assumed that the majority of maize is produced by high-input farms with sufficient nutrient supply, so CWU estimates over large scales are unlikely to be significantly affected (Mialyk et al, 2022).

1-2-5-Agriculture of tomato, maize and wheat in the Mediterranean Region

The Mediterranean region, known for its diverse climate and rich agricultural heritage, faces significant challenges due to climate change. The cultivation of key crops like winter wheat and tomato is particularly impacted, necessitating a detailed understanding of how these changes affect crop water requirements, irrigation needs, and yield outcomes.

Tomato Cultivation

Tomato cultivation in the Mediterranean region is particularly vulnerable to the effects of climate change, especially water scarcity. The study by Katerji et al. (2013) provides valuable insights into the impact of different irrigation strategies on tomato crops grown in Southern Italy. One of the key findings from this study is the significant variation in evapotranspiration (ET) under different water stress conditions. Under full irrigation, the seasonal ET for tomatoes aligns closely with control treatments. However, under severe water stress, ET values drop markedly, indicating the reduced water uptake by plants under such conditions. The AquaCrop model used in the study, while effective under non-stressed conditions, tends to underestimate ET under severe stress, highlighting the model's limitations in predicting water use under extreme conditions.

The impact of water stress on tomato yield is profound. In the control treatment, where water supply is optimal, both biomass and fruit yield are high. However, under moderate and severe stress conditions, yields decrease significantly. In the study, moderate stress resulted in a yield reduction of about 37%, while severe stress led to a reduction of up to 69%. This contrast underscores the critical importance of water availability for maintaining tomato productivity (Katerji et al, 2013).

Tomato crops, typically grown in the spring-summer period, also face significant challenges due to climate change. In the study by (Saadi, et.al, 2014) the length of the crop season (LCS) for tomatoes is projected to decrease by about 12 days on average, from 125 days in 2000 to 113 days in 2050. This reduction in LCS is primarily driven by increased temperatures, which accelerate the crop development stages. The seasonal evapotranspiration (ETc) for tomatoes under optimal water supply conditions ranges from 391 to 907 mm in 2000 and is expected to decrease to between 389 and 871 mm by 2050. The average reduction across the region is approximately 30 mm per season, or 5%. This reduction is consistent with the shorter growing season and higher temperatures, which reduce the overall water demand of the crop.The seasonal evapotranspiration (ETc) for tomatoes under optimal water supply conditions ranges from 391 to 907 mm in 2000 and is expected to decrease to between 389 and 871 mm by 2050. The average reduction across the region is approximately 30 mm per season, or 5%. This reduction is consistent with the shorter growing season and higher temperatures, which reduce the overall water demand of the crop. Interestingly, the relative yield losses for tomatoes are not expected to change significantly in the future. This stability in yield is likely due to the crop's growing period being outside the main rainy season, meaning that irrigation strategies will remain largely unchanged. However, regions experiencing the largest temperature increases and LCS reductions, such as certain areas in Turkey and Spain, may still see significant impacts (Saadi, et.al, 2014).

Maize Cultivation

Maize or corn, another vital crop in the Mediterranean region, also faces significant challenges due to water scarcity. The study by Katerji et al. (2013) reveals that corn grown under various irrigation strategies exhibits significant differences in water use and productivity. Similar to tomatoes, the seasonal ET for corn is significantly impacted by water stress. Under control conditions, ET values are consistent with expected levels, ensuring adequate water supply for optimal growth. However, under moderate and severe stress, ET values decline sharply, reflecting the reduced water availability for the crop. The biomass and grain yield of corn are equally affected by water stress. In non-stressed conditions, corn achieves high biomass and yield, but these metrics drop substantially under stress. The study shows that severe water stress can reduce corn yield drastically, with the AquaCrop model even predicting no yield under extreme conditions. This discrepancy between model predictions and actual measurements, where a yield of about 5 t/ha was recorded under severe stress, points to the need for refining predictive models to better capture the realities of extreme water scarcity (Katerji et al, 2013).

Wheat cultivation

Winter wheat in the Mediterranean region is subject to changes in climate variables that directly impact its growth cycle and water needs. Saadi, et.al, (2014) reveals in their study that between the years 2000 and 2050, the average length of the growing season for winter wheat is expected to shorten by approximately 15 days due to rising temperatures. This reduction in the growing season, combined with an overall increase in air temperature of 1.57 ± 0.27°C, affects the evapotranspiration rates and water requirements of the crop. The study shows that under optimal irrigation conditions, the evapotranspiration (ETc) of winter wheat ranges from 303 to 864 mm per season in 2000, and it is expected to slightly decrease to between 298 and 840 mm by 2050. The average decrease across the region is about 30 mm per season, equating to a 6% reduction. This decrease in ETc is largely attributed to the shortened growing season, which means less time for the crop to transpire water. The impact of these changes on crop yield is significant. Under rainfed conditions, relative yield losses (RYL) for winter wheat are expected to increase, particularly in the northern Mediterranean areas. This increase in RYL is primarily due to the reduced growing season and increased temperature, which lead to higher water stress during critical growth periods (Saadi, et.al, 2014).

1-3- Literature Review

Climate variability significantly impacts Mediterranean agriculture, particularly affecting key crops such as tomatoes, wheat, and maize. The following studies provide detailed insights into these impacts, highlighting the necessity for adaptation strategies, advanced modeling, and efficient resource management.

Chelli et al. (2022) examined how shifts in temperature and precipitation patterns induced by climate change affect the growth cycles and yield of tomato crops in the Mediterranean Basin. They concluded that adaptive management practices, such as adjusting planting dates and using heat-tolerant varieties, are necessary to sustain tomato production. This research underscores the need for adjusting agricultural practices to mitigate the adverse effects of climate change on tomato production. The study reported that tomato crops require an average crop water use (CWU) of 400-600 mm per growing season, depending on specific climatic conditions and management practices. Stratonovitch and Semenov (2022) explored the impact of extreme temperatures on wheat yield. Their study highlighted how thermal stress can significantly reduce wheat productivity, emphasizing the need for developing heat-tolerant wheat varieties and implementing adaptive agricultural practices to mitigate these effects. They concluded that integrating genetic and management adaptations is crucial for minimizing yield losses due to extreme temperatures. The study noted that wheat crops typically require a CWU of 300-500 mm per growing season, depending on local climatic conditions. Di Lena et al. (2021) highlighted the necessity for optimizing irrigation and fertilization practices to sustain tomato production under changing climatic conditions. They concluded that precision agriculture techniques can enhance water use efficiency and crop yield. The study provided practical recommendations for improving water use efficiency and crop management, noting that the water footprint (WF) for processing tomatoes ranges from 300 to 500 mm per growing season, depending on irrigation efficiency. Jägermeyr et al. (2021) focused on predicting climate change impacts on global agriculture, with a particular emphasis on wheat yields. Their research shows that new generations of climate and crop models are essential for accurately predicting the timing and severity of climate impacts. They concluded that significant yield losses can be mitigated through breeding and management adaptations. The study underscored the critical role of extreme temperature events in reducing wheat productivity, but specific water use data for wheat was not detailed. Bassu et al. (2021) analyzed various maize crop models to understand their responses to different climate change factors. Their study revealed significant variations in model predictions, highlighting the complexity of predicting maize yield responses to climate variability. They concluded that multi-model approaches provide better insights for developing robust adaptation strategies. The research indicated that maize crops in the Mediterranean typically require a CWU of 500-700 mm per growing season. Tamea et al. (2021) explored the temporal and spatial variations in the unit water footprint (uWF) of crop production from 1961 to 2016. Their study revealed significant improvements in the water efficiency of crop production over time, with marked reductions in the uWF for major crops like wheat. The analysis showed that improvements in agricultural practices and socio-economic conditions have contributed to these changes. The study also emphasized the importance of considering the temporal variability of uWF in long-term agricultural and environmental planning. This comprehensive dataset and analysis provide valuable insights for developing strategies to enhance water use efficiency in agriculture under changing climatic conditions. Blanco et al. (2020) emphasized the importance of developing and implementing adaptation strategies to manage the impacts of climate variability and change. They concluded that a combination of technological, institutional, and policy measures is required to ensure the resilience of Mediterranean agriculture. The research focused on the complex interplay between different adaptation measures and their effectiveness in maintaining agricultural productivity under changing climate conditions. González-Sampériz et al. (2019) provided a detailed account of historical climate changes and their effects on vegetation patterns. They concluded that understanding past climate variability is crucial for predicting future trends and developing effective adaptation strategies for agriculture. This historical perspective was crucial for understanding current climate trends and their potential impacts on agriculture in the Mediterranean. Tesfaye et al. (2017) assessed the potential impacts of climate change on maize systems in sub-Saharan Africa, offering relevant insights for the Mediterranean region. Their study emphasized the severe impacts of climate variability on maize yields and the necessity for adaptation strategies to maintain food security. They concluded that improving crop management and breeding for drought-resistant varieties are essential to mitigate adverse effects. The study suggested a potential increase in the water footprint for maize due to increased evapotranspiration rates under warming scenarios. Lionello et al. (2014) discussed the overall climate change impacts on the Mediterranean region. Their research highlighted the need for ongoing research and adaptive strategies to cope with the anticipated changes in climate, which are expected to significantly impact agricultural productivity. They concluded that a coordinated regional approach is required to effectively address the challenges posed by climate change. Water use for crops in the Mediterranean region was highlighted as a critical factor, with projected increases in water demand due to climate variability. Tuninetti et al. (2015) conducted a study on the global sensitivity of high-resolution estimates of crop water footprint. They examined the spatial variability of the virtual water content (VWC) of crops, particularly focusing on wheat, rice, maize, and soybean, to assess the sensitivity of VWC estimates to various parameters such as climate, soil, and agricultural practices. The study highlighted that food production heavily relies on green water (>90%), but irrigation can make crop production more water-efficient. The sensitivity analysis indicated that wheat is most sensitive to the length of the growing period, rice to reference evapotranspiration, and maize and soybean to the crop planting date. This research underscores the importance of spatial variability and the need for high-resolution modeling to accurately estimate and manage the crop water footprint. Daccache et al. (2014) investigated the water and energy footprint of irrigated agriculture in the Mediterranean region. Their study underscored the resource-intensive nature of Mediterranean farming and the pressing need for efficient resource management to adapt to climate variability and ensure sustainable agricultural practices. They concluded that adopting water-saving technologies and practices is vital for reducing the environmental footprint of agriculture. The study reported that the water footprint of irrigated agriculture in the Mediterranean can range from 600 to 1200 mm per growing season, depending on the crop and irrigation methods used.

1-4-Gaps in the past studies

Despite significant research into the water footprint and climate impacts on agriculture, there remains a notable gap concerning the standardization of water footprint assessments, particularly for Mediterranean crops such as tomatoes and cereals.

Current literature highlights variability in reported water footprint values and methodologies used across different studies. While some studies provide insights into water use efficiency and footprints, inconsistencies persist due to diverse methodologies and regional-specific factors. However, these studies did not comprehensively account for blue water from capillary rise in rainfed areas, leading to potential underestimations of water use in certain Mediterranean contexts.

Moreover, existing assessments often suffer from uncertainties related to input data, resulting in significant regional variations (±30%) in reported water footprints (Mialyk et al., 2023). These uncertainties prevent the ability to accurately compare water use efficiencies and sustainability practices across different Mediterranean regions and crop types. Therefore, a critical gap in the current literature lies in the need to standardize methodologies for assessing water footprints specific to Mediterranean agriculture.

1-5- Model of the study

The model of this study is AquaCropEarth@lternatives (ACEA) obtained from the study of (Mialyk et al., 2023). ACEA is a global process-based crop model from 1990 to 2019 at a 5 arcminute resolution representing a significant advancement in assessing water footprints (WFs) of 175 crops worldwide. This model simulates daily crop growth and water balance, considering local environmental conditions, crop characteristics, and farm management practices. It distinguishes between green water (from precipitation) and blue water (from irrigation or capillary rise) and evaluates both rainfed and irrigated systems. Outputs are NetCDF maps including unit water footprints, total water footprints of production, and crop water use, providing crucial insights into agricultural water consumption patterns. NetCDF maps showing unit water footprints will be analyzed using Python to create crop water use maps for tomatoes, maize, and wheat across the Mediterranean Sea regions and Italy. This analysis aims to evaluate how climate variability influences agricultural water consumption in these areas.

Data

The data used in this research is fundamental to the analysis and findings presented in this thesis. This chapter offers a thorough overview of the data sources, collection methods, and key characteristics, aiming to provide transparency and facilitate the replication of the study. Specifically, the data encompasses both input data and recorded outputs from the ACEA model, derived from the study conducted by Mialyk et al. (2023).

2-1- Data sources

The primary data for this study was obtained from the ACEA model as documented in Mialyk et al. (2023). The model outputs, including water footprint measurements, were essential for analyzing water usage in tomato, maize and wheat cultivation across the Mediterranean basin and Italy.

2-2- Data collection

Data collection comprises two main components:

Input data: This includes crop modeling and post- processing data such as climatic variables, soil properties, crop management practices and harvested area sourced from the National Agricultural Statistics Service (NASS), the Food and Agriculture Organization (FAO), and various peer-reviewed articles.

Model outputs: These are generated by running the ACEA model with the specified input data, simulating the unit water footprint of tomato, maize and wheat crops and producing annual water usage estimates from 1990 to 2019.

2-3- Data description

The dataset includes both input and output variables:

2-3-1- Input data

The first set of inputs encompasses historical climate data such as daily rainfall, temperature, surface shortwave radiation, wind speed, and relative humidity, sourced from the ISIMIP3 project's GSWP3-W5E5 dataset. These data were utilized to calculate reference evapotranspiration using the Penman-Monteith equation. Atmospheric CO_2 concentration data were assumed to be uniformly distributed worldwide.

Crop calendars specifying planting and harvest dates for various crops were obtained primarily from Jägermeyr et al. (2018) and other agronomic sources, ensuring adjustments for climatic variability within the ACEA model. The model allowed for flexibility in extending growing seasons by up to 15% during colder years and adjusting harvest dates based on accumulated heat units in warmer years. Fallow periods were accounted for by assuming the presence of cover crops to mitigate soil erosion.

Core crop parameters were derived from AquaCrop for ten default crops, with additional parameters for 45 core crops obtained from literature sources or expert-generated based on regional cultivar variations. Soil profiles were detailed with depths up to 3 meters, divided into compartments reflecting soil texture data from ISIMIP3. Shallow groundwater levels, essential for rainfed crops, were interpolated from monthly averages, while deeper aeration was ensured by assuming drained soils down to 1 meter.

Irrigation practices—surface, sprinkler, and drip—were tailored for each crop, with irrigation timing regulated by specific soil moisture depletion thresholds within the root zone. Thresholds varied depending on crop water stress sensitivity, with rice uniquely simulating flooded conditions and additional soil bunds to prevent runoff. Distribution data for crop growing areas, distinguishing between rainfed and irrigated lands, were sourced from SPAM2010 and GAEZ+2015.

These inputs collectively form the basis for the comprehensive simulation of crop water use and yield within the ACEA model, emphasizing the integration of diverse climatic, agronomic, and soil parameters to enhance accuracy and applicability across various agricultural settings (Mialyk et al, 2023).

In the post-processing phase, the uWF for each crop, grid cell, and year was estimated by dividing either green or blue CWU by the corresponding crop yield. Emphasis was placed on the harvest year, necessitating the aggregation of CWU over different calendar periods, particularly for crops planted in one year but harvested in another, like winter wheat. Modeled yields were initially converted from dry to fresh units using crop water content fractions, followed by their adjustment to align with national statistics from the FAOSTAT database, noting that fodder crop statistics required an older database version extrapolated linearly to fill gaps.

Both rainfed and irrigated uWFs were calculated by summing their respective green and blue components. In rainfed systems, blue uWF was represented as water from capillary rise, while in irrigated systems, it encompassed water from both irrigation and capillary rise (applicable to rice). The pWF was estimated by multiplying uWF by the corresponding annual crop production. National uWF values were derived using production-weighted averages, while CWU and crop yield calculations were performed using harvested area-weighted averages.

Scaling methods, similar to those used in (Mialyk et al, 2022), included the scaling of harvested areas and crop yields. For harvested areas, rainfed and irrigated areas specific to each crop were projected using SPAM2010 data across 1990–2019 and adjusted to match FAOSTAT values. Crop yields were scaled by multiplying fresh yields by scaled harvested areas to simulate crop production within each country, subsequently normalized to match FAOSTAT data. This national scaling factor applied adjustments uniformly across the entire country, such as halving rainfed and irrigated crop yields if the scaling factor was 0.5. This procedure allowed for the consideration of historical agricultural developments not captured by ACEA, such as increased fertilizer use, improvements in irrigation and machinery, and advancements in crop varieties and pest control. CWU scaling was considered unnecessary as it remains largely unaffected by agricultural changes compared to yield variations (Mialyk et al, 2023).

Table 2-1 summarizes the essential input data required for running the crop model and subsequent post-processing steps (Mialyk et al, 2023).

Table 2-1- Input data for crop modeling and post-processing

Data Input	Period	Timestep	Spatial Resolution	Source
For crop modeling				
Climate variables	1990–2019	Daily	30 arcminute	GSWP3-W5E5
Atmospheric CO2 concentration	1990–2019	Annual	Global	NOAA
Crop calendar	—	—	30 arcminute	(Jägermeyr et al, 2021) and crop-specific literature
Crop parameters	—	—	—	Default AquaCrop crop files, crop-specific literature, and expert knowledge
Soil composition	—	—	30 arcminute	ISIMIP3 based on Harmonized World Soil Database 1.2
Groundwater levels	2004–2014	Average monthly	5 arcminute	Fan et al, 2013
Irrigation management	2004–2009	Average		Jägermeyr et al, 2015
For post-processing				
Harvested areas	2010	Annual	5 arcminute	SPAM2010, GAEZ+2015
Irrigated cropland	1985–2005	5-year	5 arcminute	HID
Irrigated and rainfed croplands	1980–2017	10-year till 2000, then annual	5 arcminute	HYDE 3.2
Crop production statistics	1990–2019	Annual	National	FAOSTAT

Simulation setup for tomato, maize and wheat production

Three crops listed in FAOSTAT, representing 2 crop groups—cereals and fruit—were selected. These crops have sufficient input data for crop modeling (such as harvested area distribution, crop parameterization, and calendars) were chosen. For each core crop, ACEA was run to obtain CWU and crop yields. Crop modeling was performed at a 30 arcminute resolution (~50 km around the equator) with a daily time step starting from January 1, 1988. This earlier start allowed for a two-year warm-up period to generate initial soil moisture by 1990. Simulations continued until the end of 2019, including fallow periods to account for soil moisture changes between crop-growing seasons. The 30 arcminute outputs were then allocated among corresponding 5 arcminute grid cells (~8.3 km around the equator) according to the distribution of rainfed and irrigated areas from SPAM2010 (Mialyk et al, 2023).

2-3-2- Output data

Two datasets recorded from (Mialyk et al, 2023) were used in this study which encompass national average unit Water Footprints (uWF) for all 3 crops and global gridded unit Water Footprints (uWF).

The national unit Water Footprints of crops

This file is formatted as a CSV (comma-separated values) and contains annual values spanning from 1990 to 2019. The data resolution is national, with countries listed according to the FAOSTAT database. This dataset includes green and blue uWF alongside related variables for 3 crops. Additionally, Crop Water Use (CWU) can be derived by multiplying the uWF with the crop yield and further dividing by 10. Figures 2-1, 2-2 and 2-3 present the average unit water footprint, yield and crop water use of tomato, maize and wheat in Mediterranean countries from 1990 to 2019.

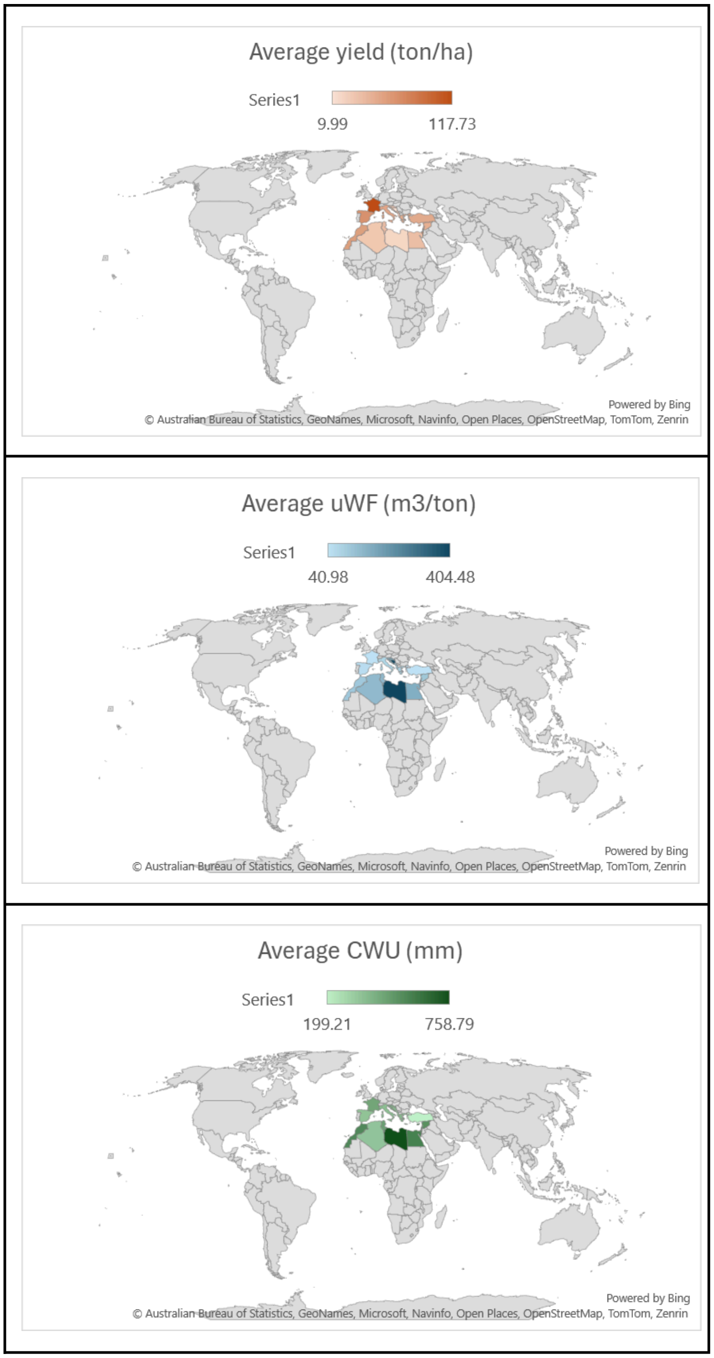
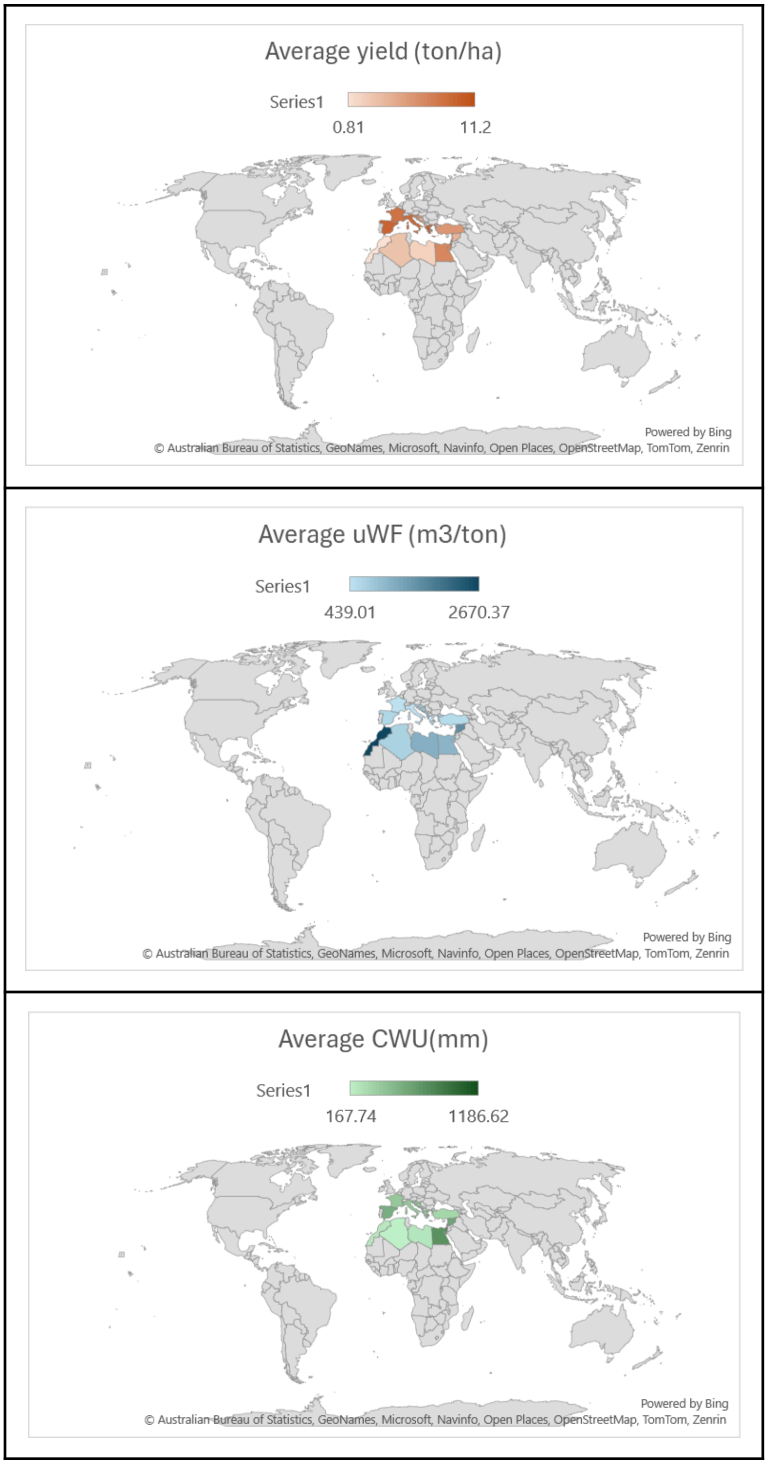


Figure 2-1- Average Yield, uWF and CWU of tomato in Mediterranean countries

As can be seen in the above figure, Libya has the highest average uWF and CWU of tomato from 1990 to 2019 between Mediterranean countries.


Average yield (ton/ha)

Average uWF (m3/ton)

Average CWU(mm)

Figure 2-2- Average Yield, uWF and CWU of maize in Mediterranean countries

As can be seen in the above figure, Morocco and Israel have the highest average uWF and CWU of maize ,respectively, from 1990 to 2019 between Mediterranean countries.

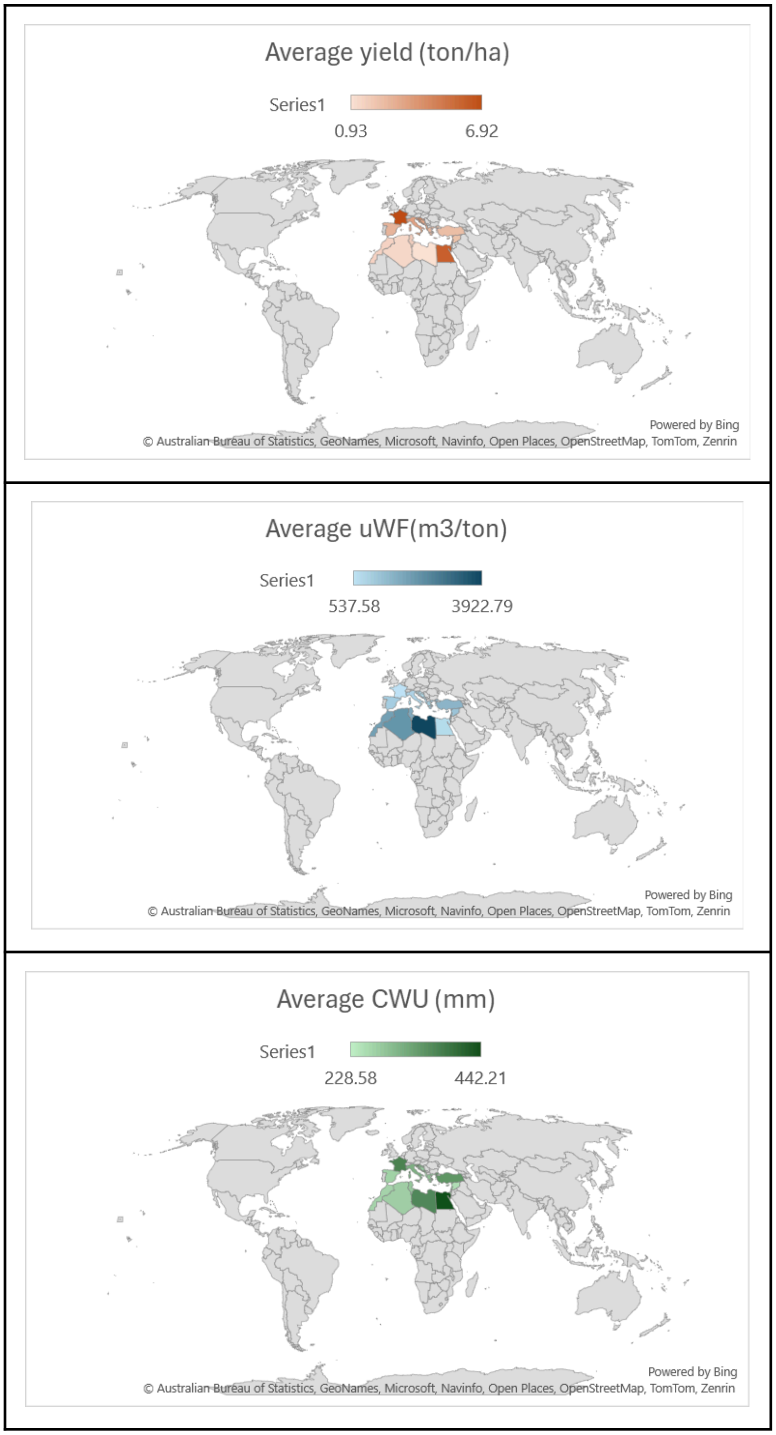


Figure 2-3- Average Yield, uWF and CWU of wheat in Mediterranean countries

As can be seen in the above figure, Libya and Egypt have the highest average uWF and CWU of wheat ,respectively, from 1990 to 2019 between Mediterranean countries.

The global gridded unit Water Footprints of crops

These are stored in 9 separate files for each crop. The files are formatted in NetCDF4, with values covering the period from 1990 to 2019. The spatial extent of this data is global, ranging from 180°E to 180°W and 90°S to 90°N, aligned with the WGS84 coordinate system. The resolution is set at 5 arcminutes (0.083333 decimal degrees), which translates to 4320 columns and 2160 rows.

Each of these files contains 30 layers that detail the total unit water footprint (uWF), rainfed_blue water footprint, rainfed_green water footprint, irrigated_blue water footprint, irrigated_green water footprint of the corresponding crop, measured in cubic meters per ton per year (m^3 t^{-1} yr^{-1}), rainfed_ unscaled yield, irrigated_ unscaled yield, total_ unscaled yield (t ha^{-1} yr^{-1}) and scaling factors during thirty years.

Figures 2-4, 2-5 and 2-6 show the average uWF of tomato, maize and wheat in the Mediterranean region from 1990 to 2019.

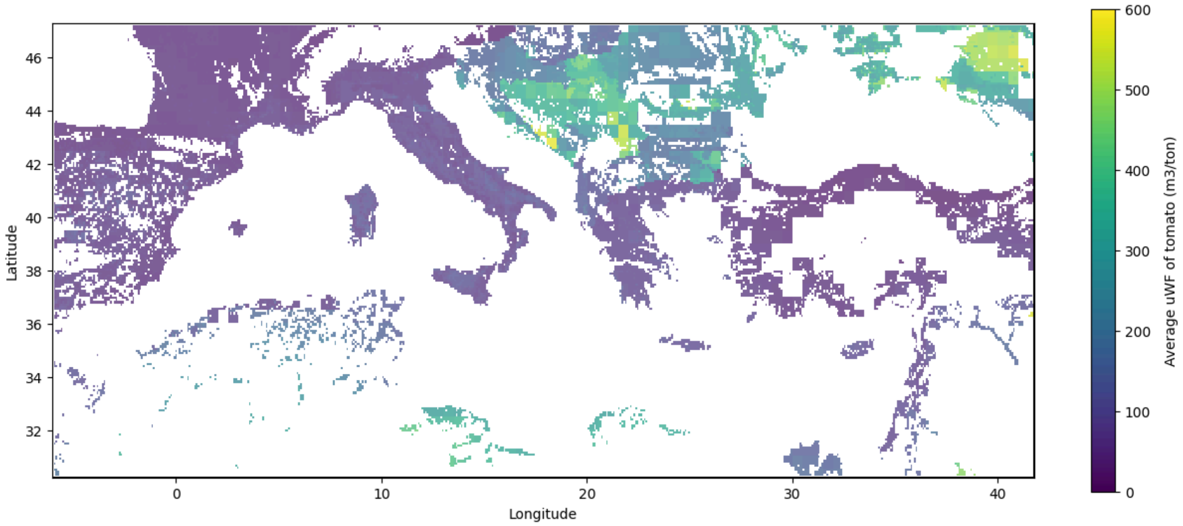


Figure 2-4- Average uWF of tomato in Mediterranean region (1990-2019)

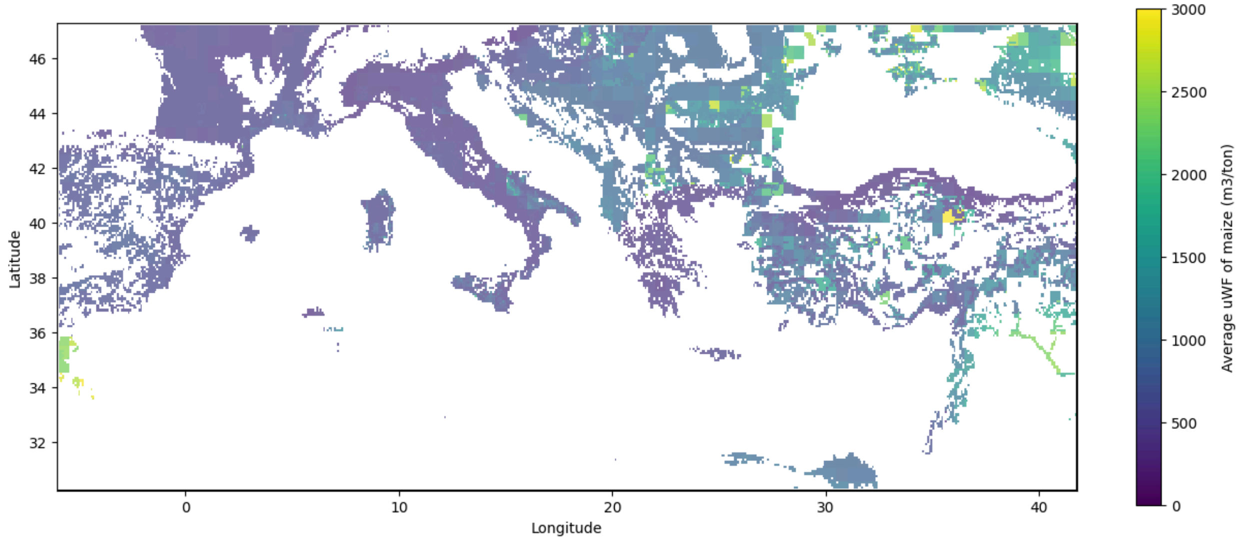


Figure 2-5- Average uWF of maize in Mediterranean region (1990-2019)

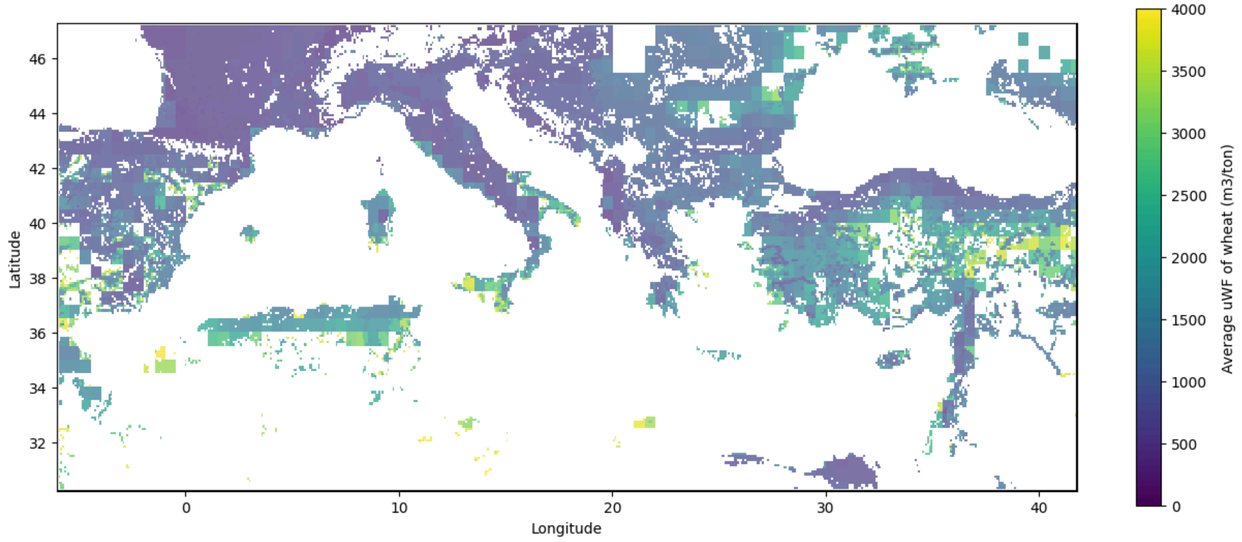


Figure 2-6- Average uWF of wheat in Mediterranean region (1990-2019)

As can be seen in these figures, the average uWF of wheat is more than other crops in this region from 1990 to 2019.

Figure 2-7 shows the average uWF of tomato, maize and wheat in Italy from 1990 to 2019.

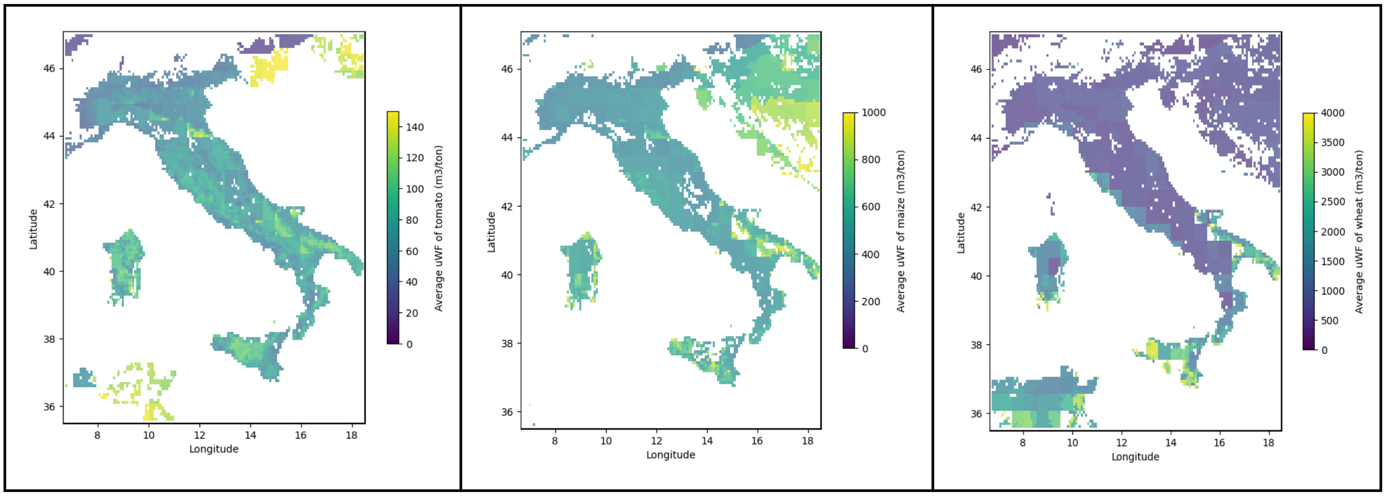


Figure 2-7- Average uWF of tomato, maize and wheat in Italy (1990-2019)

As can be seen in this figure, the average uWF of wheat is more than other crops in this country from 1990 to 2019.

Analysis of crop water use of tomato, maize and wheat in the Mediterranean region and Italy will be done in the Chapter of Results.

Methods

This chapter details the methodology employed in analyzing the crop water use (CWU) of tomato, maize, and wheat in the Mediterranean region and Italy from 1990 to 2019. The analysis focuses on various statistical measures, including average, standard deviation, coefficient of variation, p-value of the trends, and slope of the trends. This section outlines the data sources, tools and software used, and the detailed steps involved in the analysis, providing a comprehensive framework for understanding the approach and ensuring reproducibility of the results.

3-1-Recorded data

The primary data for this study are raster datasets representing the CWU for tomato, maize, and wheat over the Mediterranean region and Italy. These raster datasets are sourced from the recorded rasters including total water footprint, unscaled yield, and scaling factors of tomato, maize, and wheat by Mialyk et al. (2023).

3-2- Tools and software

Several tools and software packages are used for data processing, analysis, and visualization. The primary tools and software include:

QGIS

QGIS (Quantum Geographic Information System) is employed for the initial raster calculations and spatial data management. QGIS is an open-source geographic information system that provides powerful tools for mapping, spatial analysis, and data visualization. It facilitates the preparation and preprocessing of raster data, including clipping, reprojecting, and calculating derived rasters for CWU.

Python

Python is the main programming language used for statistical analysis and plotting. Python's versatility and extensive library support make it ideal for handling complex data analysis tasks. The following Python libraries are used:

- **Rasterio:** For reading, writing, and manipulating raster datasets. Rasterio provides efficient tools for handling geospatial raster data, enabling seamless integration with other data analysis workflows.
- **Matplotlib:** For plotting and visualizing data. Matplotlib is a widely used plotting library that offers extensive customization options for creating publication-quality graphs and charts.

- **Geopandas:** For handling geospatial data. Geopandas extends the capabilities of pandas (a powerful data analysis library) to include geospatial operations, making it easy to work with geographic data within a familiar data analysis framework.
- **Numpy:** For numerical calculations. Numpy provides support for large, multi-dimensional arrays and matrices, along with a collection of mathematical functions to operate on these arrays efficiently.
- **Scipy:** For statistical analysis. Scipy builds on Numpy by adding a collection of algorithms and functions for advanced scientific and technical computing, including statistical tests, optimization, and signal processing.
- **Shapely:** For geometric operations. Shapely facilitates the manipulation and analysis of planar geometric objects, making it easy to perform spatial operations such as intersection, union, and buffering.

3-3-Data processing

The data processing begins with raster calculations in QGIS. The initial processing of raster datasets involves the following steps:

3-3-1-Loading and visualizing raster data

The total unit water footprint, unscaled yield and scaling factors rasters for each crop (tomato, maize, and wheat) are loaded into QGIS.

3-3-2-Calculating derived rasters

To calculate CWU(mm) rasters for each crop, the following formula is used:

$$\mathrm{CWU(mm)} = \{(\mathrm{unscaled\_yield}\ (\mathrm{t/ha}))*(\mathrm{scaling\_factors})*(\mathrm{uWF}\ (\mathrm{m^3/t}))\} / 10$$

Unscaled yields represent the maximum attainable water-limited yields. To derive actual yields, they need to be scaled by multiplying with "scaling factors". The rasters for 30 years are saved in .tif format. These 30 rasters for each crop are the input for further analysis in Python. Figure 3-1 shows the panel of CWU of tomato in Italy during 1990, 2005, 2019 and average CWU between 2010 to 2019.

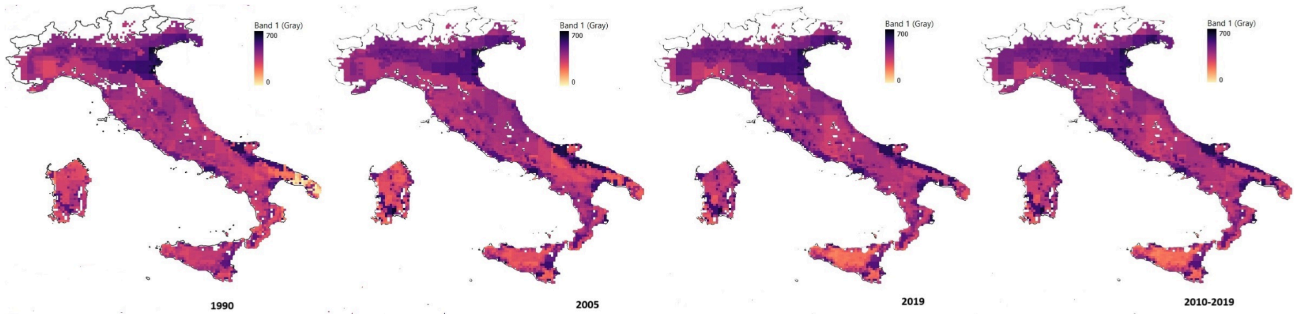


Figure 3-1- Panel of CWU of tomato in Italy

The processed raster datasets are then exported from QGIS for further analysis in Python. Each raster dataset is saved in a format compatible with the Rasterio library, ensuring seamless integration with the Python analysis workflow. Using the Rasterio library, the CWU raster datasets are loaded into Python. This library enables efficient reading and manipulation of the raster data, facilitating the subsequent statistical analysis. The CWU data are extracted from the raster files, ready for detailed examination.

3-3-3-Statistical analysis

The statistical analysis commences with the calculation of averages and standard deviations for CWU across the study period. These measures provide insights into the central tendency and dispersion of CWU values for each crop. The calculations are performed using the Numpy library, which offers efficient array operations and statistical functions.

The coefficient of variation is then calculated to assess the relative variability of CWU. The coefficient of variation is a normalized measure of dispersion, expressed as a percentage of the mean. It provides a useful comparison of variability across different crops and regions. The calculation is performed as follows:

$$\text{coefficient\_of\_variation} = \text{std\_deviation\_cwu} / \text{average\_cwu}$$

Trend analysis is performed to identify temporal patterns in CWU. Linear regression is employed to determine the slope and significance (p-value) of the trends. This analysis reveals whether CWU for each crop exhibits an increasing or decreasing trend over time and the statistical significance of these trends. The Scipy library provides functions for performing linear regression and calculating associated statistics.

3-3-4-Visualization

The results are visualized through gridded maps with pixels in PNG format, depicting the spatial distribution of CWU across the Mediterranean region and Italy. These maps are created using the Matplotlib library, showcasing the average CWU for each crop over the 30-year period. The visualizations highlight regional variations and trends, offering a clear graphical representation of the data.

Geopandas is used for handling and plotting geospatial data, ensuring accurate application of the bounding boxes for the Mediterranean region and Italy. The bounding boxes define the spatial extent of the analysis, and Geopandas facilitates the visualization of these areas on the maps. The combination of Matplotlib and Geopandas provides a powerful toolkit for creating detailed and informative visualizations. Example code for visualizing the bounding boxes using Geopandas is as follows:

Define the bounding boxes for Mediterranean region and Italy:

bounding_box = box(minx, miny, maxx, maxy)
minx, miny, maxx, maxy = -6.0325, 30.2316, 41.7783, 47.2866
bounding_box = box(minx, miny, maxx, maxy)
minx, miny, maxx, maxy= 6.6269, 35.4938, 18.5189, 47.0918

3-4-Example code of P-value of the trend

Following codes are for P-value of crop water use of wheat in Mediterranean region:

```
import os
import rasterio
import numpy as np
import matplotlib.pyplot as plt
from shapely.geometry import box
import geopandas as gpd
from rasterio.mask import mask
from scipy.stats import linregress, t

# Set random seed for reproducibility
np.random.seed(42)

# Define the bounding box coordinates for Mediterranean countries
minx, miny, maxx, maxy = -6.0325, 30.2316, 41.7783, 47.2866  # Adjust these coordinates as needed
bounding_box = box(minx, miny, maxx, maxy)
```

```
# Create a GeoDataFrame from the bounding box
geo = gpd.GeoDataFrame({'geometry': bounding_box}, index=[0],
crs='EPSG:4326')

# List of file paths to your 30 raster images
directory = './files'
raster_files = sorted([os.path.join(directory, file) for file in
os.listdir(directory) if file.endswith('.tif')])

# Function to read and mask raster files to the bounding box
def read_and_mask_raster(file_path, bbox):
    with rasterio.open(file_path) as src:
        out_image, out_transform = mask(src, [bbox], crop=True)
        return out_image[0]  # assuming the raster has a single band

# Read and mask all raster files into a 3D NumPy array
maps = np.array([read_and_mask_raster(file_path, bounding_box) for
file_path in raster_files])

# Shape of the raster images
n_years, n_rows, n_cols = maps.shape
print(f"Shape of maps: {maps.shape}")

# Flatten the 2D array of maps
flattened_maps = maps.reshape(n_years, -1)  # Shape: (30, n_rows * n_cols)

# Initialize an array to store p-values for each pixel
p_values = np.empty(flattened_maps.shape[1])
p_values.fill(np.nan)  # Initialize with NaNs

# Perform linear regression for each pixel
years = np.arange(1990, 2020)
for i in range(flattened_maps.shape[1]):
    data = flattened_maps[:, i]
    valid_data = np.isfinite(data)  # Only use non-NaN data points for
regression
    if np.sum(valid_data) > 1:  # Ensure at least 2 non-NaN values for
regression
        slope, intercept, r_value, p_value, std_err =
linregress(years[valid_data], data[valid_data])
```

```
        if std_err != 0:  # Check if std_err is not zero
            t_statistic = slope / std_err
            df = np.sum(valid_data) - 2  # degrees of freedom
            p_value_ttest = t.sf(np.abs(t_statistic), df) * 2  #
two-tailed p-value
            p_values[i] = p_value_ttest

# Reshape the p-values array back to the original raster shape
p_values_reshaped = p_values.reshape(n_rows, n_cols)
print(f"Shape of p_values_reshaped: {p_values_reshaped.shape}")

# Create a mask for significant and insignificant p-values
alpha = 0.05
significant_mask = p_values_reshaped < alpha
insignificant_mask = p_values_reshaped >= alpha

# Replace NaNs with a specific high value for visualization purposes
p_values_reshaped[np.isnan(p_values_reshaped)] = 1  # Assuming 1 is
outside your significant range

# Plot the p-values on the map
fig, ax = plt.subplots(figsize=(12, 10))

# Plot insignificant pixels in white
ax.imshow(insignificant_mask, cmap='binary', interpolation='nearest',
alpha=0.5, extent=(minx, maxx, miny, maxy))

# Plot significant pixels in a colormap (e.g., 'viridis')
significant_values = np.where(significant_mask, p_values_reshaped, np.nan)
cax = ax.imshow(significant_values, cmap='viridis',
interpolation='nearest', alpha=0.7, extent=(minx, maxx, miny, maxy),
vmin=0, vmax=alpha)

# Add colorbar for p-values
cbar = fig.colorbar(cax, ax=ax, fraction=0.035, pad=0.04)
cbar.set_label('P-values of CWU of wheat', labelpad=10)  # Adjusted label
padding for spacing
cbar.set_alpha(1)
cbar.draw_all()
```

```
# Plot the bounding box
geo.boundary.plot(ax=ax, edgecolor='black')

# Add legend for significant and insignificant pixels
from matplotlib.patches import Patch
legend_elements = [Patch(facecolor='gray', edgecolor='black',
label='Insignificant'),
                   Patch(facecolor='white', edgecolor='black',
label='Significant (See colorbar)')]

# Position the legend outside the plot area at the bottom left
plt.legend(handles=legend_elements, loc='upper left', bbox_to_anchor=(0, -0.1),
frameon=True)

# Remove the title from the map
ax.set_title('')  # Ensure the title is removed

plt.xlabel('Longitude')
plt.ylabel('Latitude')
plt.grid(False)
plt.tight_layout()

# Adjust the subplot parameters to maximize the map area
fig.subplots_adjust(left=0.05, right=0.95, top=0.95, bottom=0.05)
# Manually adjust the colorbar height
cbar.ax.set_aspect('auto')
cbar.ax.set_position([0.92, 0.05, 0.02, 0.9])  # [left, bottom, width,
height]

plt.show()
```

The maps and plots which are derived from the codes and saved in PNG format will be shown in the next chapter.

Results

In this chapter, the impact of climate change on crop water use (CWU) for tomato, maize, and wheat across Mediterranean countries and Italy from 1990 to 2019 is investigated. Several key maps illustrating trends and variations in CWU were generated. The average CWU maps were produced to provide a baseline understanding of water usage for these crops in the region, while the standard deviation maps were created to highlight areas of significant variability. The coefficient of variation maps were developed to offer insights into the relative variability of CWU, emphasizing regions with inconsistent water use patterns. Additionally, the p-value and slope maps were generated to illustrate the statistical significance and direction of trends in CWU, respectively, revealing the extent to which climate change has influenced agricultural water requirements. These visualizations collectively underscore the diverse impacts of climate change on agricultural practices, with significant spatial variability and notable differences among the three crops studied.

4-1-Average crop water use

Average crop water use (CWU) refers to the mean amount of water consumed by a crop over a specified period and area. It is a crucial metric in agricultural and environmental studies, helping to determine the water requirements of different crops under varying climatic conditions. Typically expressed in units of water volume (e.g., millimeters), average CWU is calculated by summing the water used by the crop over the given period and dividing it by the number of observations or time points considered. This metric provides an essential baseline for understanding how much water crops need on average, aiding farmers, policymakers, and researchers in making informed decisions about water management, irrigation practices, and agricultural planning. In the context of climate change, examining average CWU can reveal how changing temperatures, precipitation patterns, and other climatic factors affect water consumption by crops, enabling better adaptation strategies to ensure sustainable agricultural productivity.

4-1-1-Average crop water use of tomato in Mediterranean Sea Basin

Figure 4-1 shows the map of average crop water use of tomato in the Mediterranean Sea Basin.

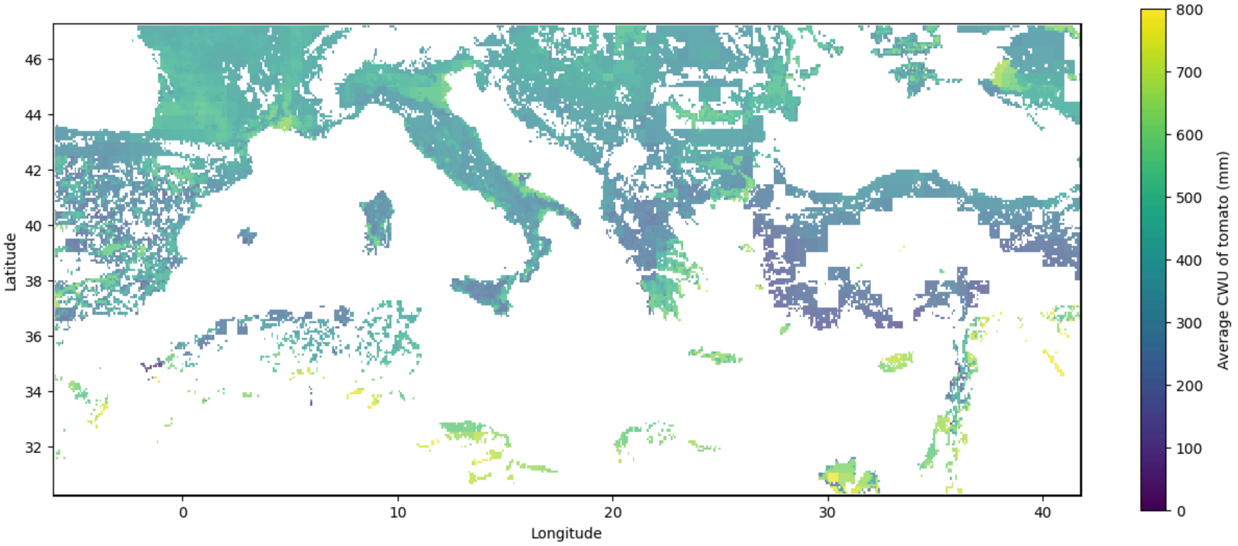


Figure 4-1-Average crop water use of tomato in Mediterranean Sea Basin (1990-2019)

The map presented shows the average crop water use (CWU) of tomatoes across Mediterranean countries from 1990 to 2019. The color scale on the right indicates the CWU in millimeters (mm), ranging from 0 to 800 mm. The interpretation of this map involves analyzing the spatial distribution of water use by tomato crops over the specified period.

Regions depicted in green to yellow colors represent areas where the average crop water use (CWU) of tomatoes is higher, approaching 800 mm. These areas are primarily concentrated in southern Spain, southern Italy, parts of Greece, and along the Mediterranean coast of Turkey. This distribution suggests that these regions have conditions conducive to higher water consumption by tomato crops, including favorable climates, suitable soils, and effective irrigation practices. The high water use in these areas indicates intensive agricultural activities and a reliance on sufficient water availability to sustain tomato cultivation.

The blue and light blue areas on the map indicate moderate average CWU, generally between 200 mm and 500 mm. These regions are widespread across northern Mediterranean areas, such as northern Italy, parts of France, and parts of the Balkans. The moderate water use in these regions could be attributed to cooler temperatures, varying irrigation practices, or other local agricultural conditions that do not require as much water for tomato cultivation. These areas reflect a balance between sufficient water availability and efficient use, likely influenced by both climatic and management factors.

The purple and dark blue areas denote lower CWU, closer to 0 mm. These areas are scattered across the map, indicating regions where tomato cultivation may either be less intensive, involve less irrigation, or where the climate is less favorable for high water use by tomato crops. Some parts of North Africa and the interior regions of Mediterranean countries fall into this category. The lower water use in these areas suggests limitations in either natural water availability or agricultural practices that necessitate reduced water consumption for tomato production.

The map reveals a general trend where coastal and southern regions tend to exhibit higher CWU, reflecting warmer temperatures and potentially more intensive agricultural practices. Conversely, inland and northern areas have lower CWU, which could be due to cooler climates and different agricultural practices. This geographical trend underscores the influence of regional climatic conditions on agricultural water use patterns, highlighting the variability in water requirements across different parts of the Mediterranean.

4-1-2-Average crop water use of tomato in Italy

Figure 4-2 shows the map of average crop water use of tomato in Italy.

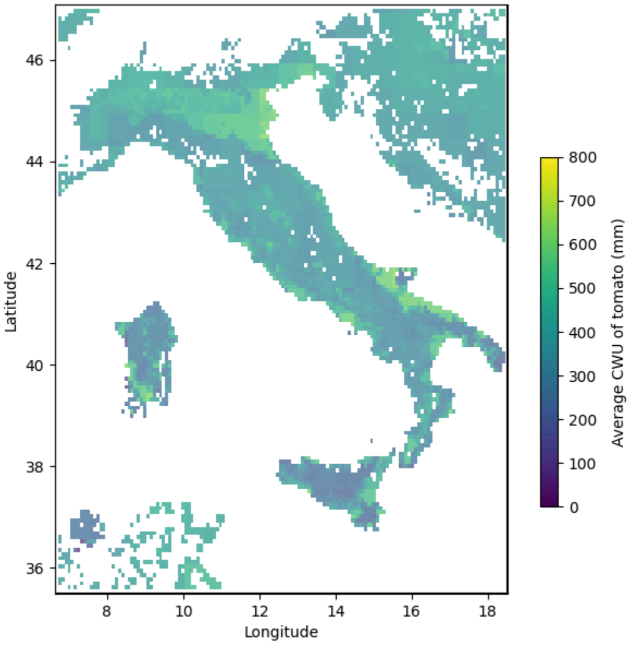


Figure 4-2- Average crop water use of tomato in Italy (1990-2019)

The map displayed illustrates the average crop water use (CWU) for tomatoes across Italy from 1990 to 2019. The color scale on the right-hand side indicates the CWU in millimeters (mm), ranging from 0 to 800 mm.

Regions shaded in green to yellow on the map represent areas where tomato crops have higher average crop water use (CWU), approaching 800 mm. These areas are primarily found in the central and southern parts of Italy, including parts of Lazio, Campania, and Sicily. This suggests that these regions have climatic conditions, soil properties, and irrigation practices that lead to higher water consumption by tomato crops. The high water use in these areas indicates not only favorable environmental conditions but also possibly intensive agricultural practices that rely heavily on water availability to maximize tomato production.

Areas depicted in shades of blue and light blue indicate moderate average CWU, generally between 200 mm and 500 mm. These regions are distributed across northern Italy, including parts of Lombardy and Emilia-Romagna, as well as scattered locations in southern Italy. This moderate water use could result from cooler temperatures, different irrigation practices, or other local agricultural conditions. In these regions, the balance between water availability and crop requirements is maintained, suggesting that agricultural practices are adapted to local climatic conditions and resources.

Purple and dark blue areas on the map show lower CWU, closer to 0 mm. These regions are less frequent and are found in scattered locations, including some parts of the northernmost and southernmost regions of Italy. Lower water use in these areas could be due to less intensive tomato cultivation, reduced irrigation, or climatic conditions less favorable for high water consumption. The lower CWU indicates that these areas may have either less favorable growing conditions for tomatoes or that farmers use more water-efficient practices, possibly due to water scarcity or other environmental constraints.

The map reveals a general trend where coastal and southern regions exhibit higher CWU, which could be attributed to warmer temperatures and possibly more intensive agricultural practices. In contrast, northern and inland areas have lower CWU, likely due to cooler climates and different farming methods. This geographical trend underscores the influence of regional climatic conditions on agricultural water use patterns, highlighting the variability in water requirements across different parts of Italy. The variation in CWU across the country reflects the diverse agricultural practices and environmental conditions that characterize Italian tomato cultivation.

4-1-3-Average crop water use of maize in Mediterranean Sea Basin

Figure 4-3 shows the map of average crop water use of maize in the Mediterranean Sea Basin.

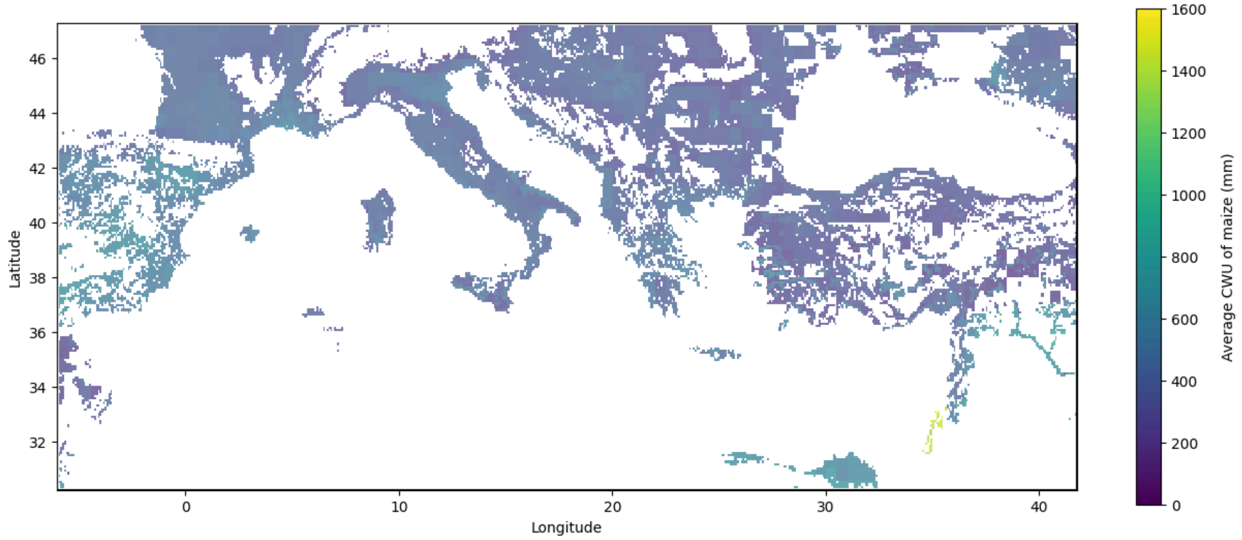


Figure 4-3-Average crop water use of maize in Mediterranean Sea Basin (1990-2019)

The map displayed shows the average crop water use (CWU) for maize in Mediterranean countries from 1990 to 2019. The color scale on the right-hand side indicates the CWU in millimeters (mm), ranging from 0 to 1600 mm.

Regions shaded in green to yellow on the map represent areas where maize crops have higher average crop water use (CWU), approaching 800 mm. These high CWU areas are notably found in parts of northern Italy, western Spain, and isolated spots in Greece and Turkey. The prevalence of these regions suggests that they have climatic conditions and agricultural practices that lead to increased water consumption for maize cultivation. Factors such as higher temperatures, fertile soils, and intensive irrigation practices likely contribute to the elevated water use, indicating a significant reliance on water resources to maintain high crop yields.

Areas depicted in shades of blue to light blue indicate moderate average CWU, generally between 400 mm and 1000 mm. These regions are widespread, covering large parts of Italy, Spain, and the western coastal areas of Turkey. This moderate water use suggests the presence of varying climatic conditions and irrigation practices that are less intense compared to the high CWU areas. The distribution of these moderate water use regions indicates a balance between the availability of water resources and the agricultural demands of maize crops, reflecting diverse agricultural practices adapted to local environmental conditions.

Purple and dark blue areas on the map show lower CWU, closer to 0 mm. These regions are scattered throughout the Mediterranean, with notable concentrations in parts of North

Africa, such as Morocco, and the eastern Mediterranean, including parts of Syria and Lebanon. Lower water use in these areas could be due to less intensive maize cultivation, reduced irrigation, or climatic conditions that are less favorable for high water consumption. The lower CWU in these regions highlights the challenges posed by limited water availability and less favorable growing conditions, necessitating more water-efficient agricultural practices.

The map shows a general trend where coastal and northern regions exhibit higher CWU, which could be attributed to favorable growing conditions, including higher rainfall or more intensive irrigation practices. In contrast, inland and southern areas have lower CWU, likely due to drier climates and different farming methods. This geographical trend underscores the influence of regional climatic conditions on agricultural water use patterns, emphasizing the variability in water requirements across different parts of the Mediterranean. The trend also reflects the diverse agricultural strategies employed to manage water resources and optimize crop production.

4-1-4-Average crop water use of maize in Italy

Figure 4-4 shows the map of average crop water use of maize in Italy.

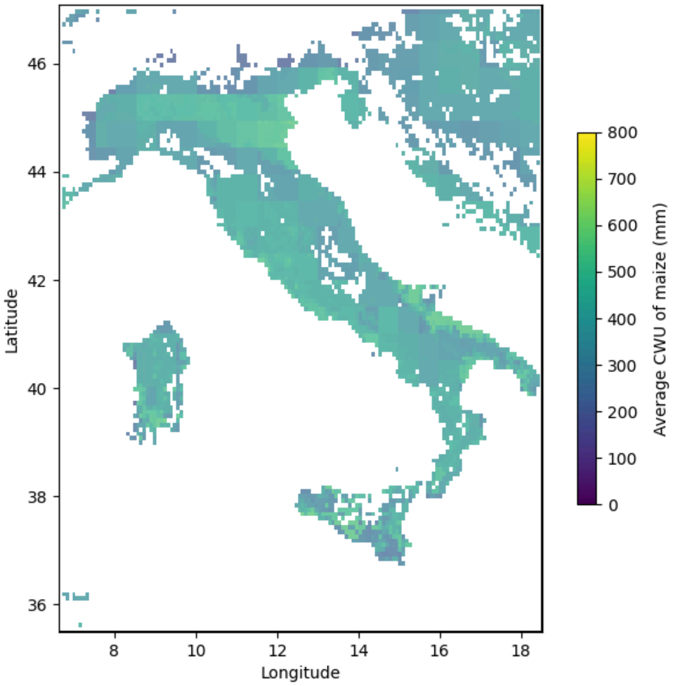


Figure 4-4- Average crop water use of maize in Italy (1990-2019)

The map illustrates the average crop water use (CWU) for maize across Italy, with values ranging from 0 mm to 800 mm as indicated by the color scale on the right. Regions are colored according to their CWU levels, with purple and dark blue representing lower CWU and green to yellow indicating higher CWU.

In Italy, regions shaded in green to yellow, indicating higher average CWU (approaching 800 mm), are primarily found in the northern parts of the country. Notable regions with high water use include parts of the Po Valley, an area renowned for its intensive agricultural activities and favorable climatic conditions that support high water consumption for maize cultivation. Additionally, some areas in central and southern Italy also exhibit higher CWU, though these regions are less extensive. The high water use in these areas suggests a significant reliance on water resources to maintain high crop yields, supported by suitable environmental conditions and effective irrigation practices.

Areas depicted in shades of blue to light blue, with moderate average CWU (generally between 200 mm and 500 mm), are widespread across Italy. These regions cover large parts of central Italy and some areas in the south. The moderate water use in these areas indicates a balance between water availability and the agricultural demands of maize crops. This distribution reflects varying climatic conditions and irrigation practices that are less intense compared to high CWU areas. The moderate CWU suggests that agricultural practices in these regions are adapted to local environmental conditions, ensuring a sustainable use of available water resources.

Regions shaded in purple and dark blue, indicating lower CWU (closer to 0 mm), are scattered throughout Italy, with notable concentrations in the southernmost regions and certain parts of northern and central Italy. Lower water use in these areas could be due to less intensive maize cultivation, reduced irrigation, or climatic conditions that are less favorable for high water consumption. The lower CWU highlights the challenges posed by limited water availability and less favorable growing conditions, necessitating more water-efficient agricultural practices in these regions.

The map shows a general trend where northern regions, particularly the fertile and agriculturally intensive Po Valley, exhibit higher CWU. In contrast, southern and some central areas tend to have lower CWU. This geographical trend underscores the influence of regional climatic conditions and agricultural practices on water use patterns, with northern Italy's more favorable growing conditions supporting higher water consumption. The variability in CWU across Italy reflects the diverse agricultural strategies employed to manage water resources and optimize crop production.

4-1-5-Average crop water use of wheat in Mediterranean Sea Basin

Figure 4-5 shows the map of average crop water use of wheat in the Mediterranean Sea Basin.

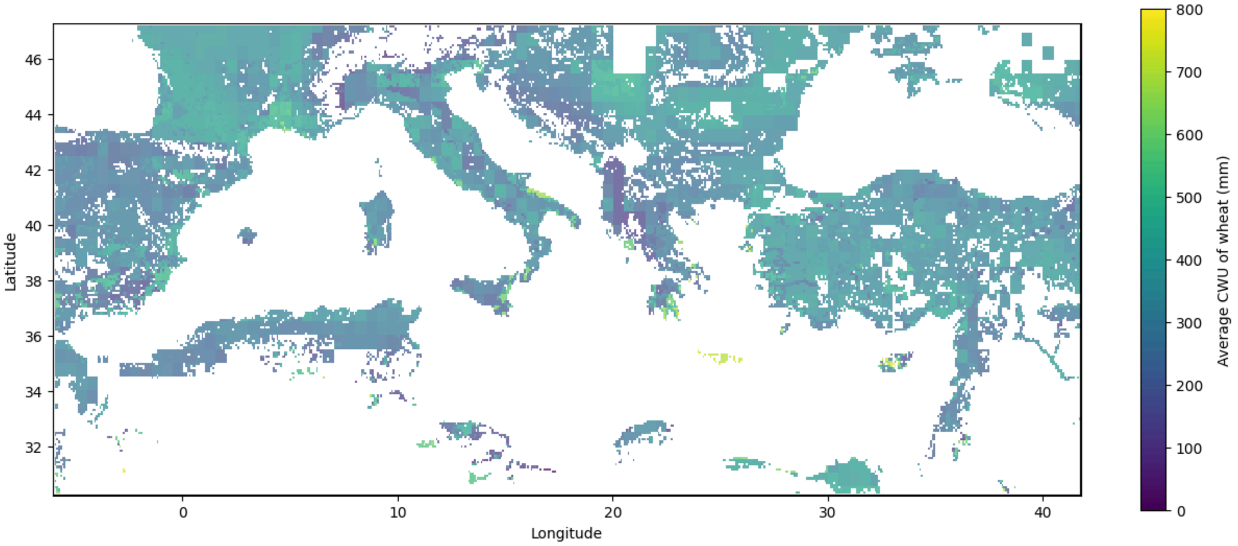


Figure 4-5-Average crop water use of wheat in Mediterranean Sea Basin (1990-2019)

The map provides a visual representation of the average crop water use (CWU) for wheat across the Mediterranean region, with values ranging from 0 mm to 800 mm, as indicated by the color scale on the right. The regions are color-coded according to their CWU levels, with purple and dark blue representing lower CWU and green to yellow indicating higher CWU.

In the Mediterranean region, areas shaded in green to yellow, signifying higher average CWU (approaching 800 mm), are relatively sparse but can be observed in specific locales. Notably, parts of southern Spain, western Turkey, and small spots in Greece exhibit these high CWU values. These regions likely have favorable climatic conditions, such as adequate rainfall and warm temperatures, coupled with agricultural practices that lead to increased water consumption for wheat cultivation. The high water use in these areas underscores the significant reliance on water resources to sustain high wheat yields.

Regions depicted in shades of blue to light blue, indicating moderate average CWU (generally between 200 mm and 500 mm), are more widespread across the Mediterranean. These areas cover large portions of northern Italy, parts of central and southern Spain, and extensive areas in Greece, Turkey, and the western coastal regions of North Africa. The moderate water use suggests a balance between water availability and agricultural demands, reflecting diverse climatic conditions and irrigation practices that are less intensive compared to the high CWU areas. This distribution indicates that these regions have adapted their wheat farming practices to local environmental conditions, ensuring sustainable use of available water resources.

Areas shaded in purple and dark blue, representing lower CWU (closer to 0 mm), are scattered throughout the Mediterranean, with notable concentrations in parts of North

Africa, including Morocco, and eastern Mediterranean regions such as Syria and Lebanon. Lower water use in these areas could be attributed to less intensive wheat cultivation, limited irrigation, or climatic conditions less conducive to high water consumption. The lower CWU in these regions highlights the challenges posed by limited water availability and less favorable growing conditions, necessitating more water-efficient agricultural practices.

The map reveals a general geographical trend where coastal and northern regions exhibit higher CWU, possibly due to favorable growing conditions, including higher rainfall or more intensive irrigation practices. In contrast, inland and southern areas have lower CWU, likely due to drier climates and different farming methods. This trend underscores the influence of regional climatic conditions on agricultural water use patterns, emphasizing the variability in water requirements across the Mediterranean. The diversity in CWU reflects the varied agricultural strategies employed to manage water resources and optimize wheat production.

4-1-6-Average crop water use of wheat in Italy

Figure 4-6 shows the map of average crop water use of wheat in Italy.

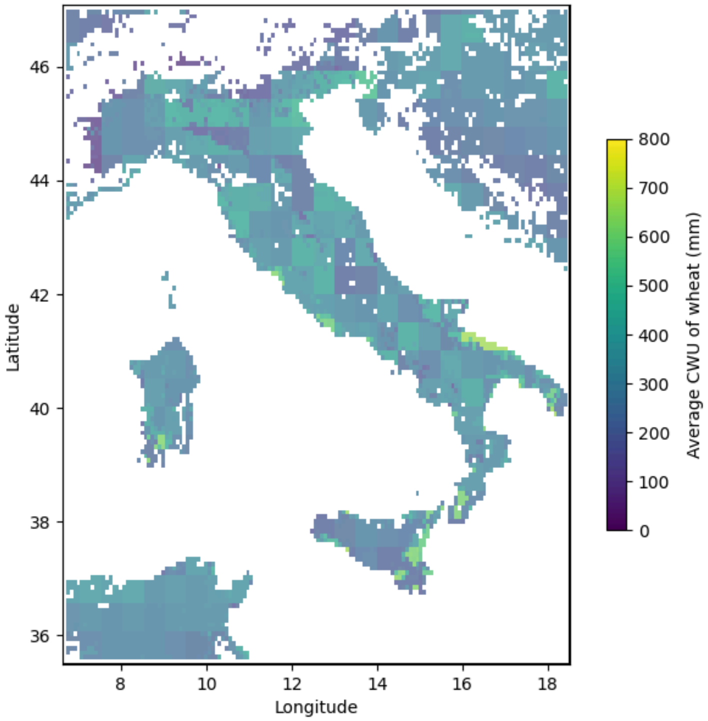


Figure 4-6- Average crop water use of wheat in Italy (1990-2019)

The map presents the average crop water use (CWU) for wheat across Italy, with values ranging from 0 mm to 800 mm as shown by the color scale on the right. The regions are color-coded to indicate their respective CWU levels, where purple and dark blue represent lower CWU and green to yellow denote higher CWU.

In Italy, regions shaded in green to yellow, which signify higher average CWU approaching 800 mm, are found primarily in the central and southern parts of the country. Notable areas with high CWU include parts of central Italy, particularly along the western coast near Lazio, and some regions in southern Italy, such as areas in Calabria and Sicily. These regions likely have climatic conditions, soil properties, and agricultural practices that lead to increased water consumption for wheat cultivation. The high water use in these areas suggests a significant reliance on irrigation and favorable environmental conditions that support intensive wheat farming.

Moderate average CWU, depicted in shades of blue to light blue (generally between 200 mm and 500 mm), is widespread across Italy. These regions cover large portions of northern Italy, including parts of the Po Valley, as well as central and southern areas. The moderate water use in these regions reflects a balance between water availability and agricultural demands. This distribution suggests that these areas have adapted their wheat farming practices to the local environmental conditions, ensuring sustainable use of available water resources. The variation in CWU within these regions may be influenced by factors such as rainfall patterns, soil types, and irrigation methods.

Regions shaded in purple and dark blue, indicating lower CWU (closer to 0 mm), are scattered throughout Italy. Notable concentrations of lower water use are found in some northernmost regions and specific parts of southern Italy. Lower water use in these areas could be attributed to less intensive wheat cultivation, limited irrigation, or climatic conditions less conducive to high water consumption. The lower CWU highlights the challenges posed by limited water availability and less favorable growing conditions, necessitating more water-efficient agricultural practices in these regions.

The map shows a geographical trend where coastal and central regions exhibit higher CWU, which could be attributed to favorable growing conditions such as higher rainfall or more intensive irrigation practices. In contrast, some northern and southern inland areas show lower CWU, likely due to cooler or drier climates and different farming methods. This trend underscores the influence of regional climatic conditions and agricultural practices on water use patterns, highlighting the variability in water requirements across Italy.

4-2- Standard deviation of crop water use

The standard deviation of crop water use (CWU) is a statistical measure that quantifies the variation or dispersion of CWU values from the mean, providing insight into how much the water use for a particular crop varies over a specific period or across different regions. A low standard deviation indicates that the CWU values are close to the mean, suggesting consistent water use, while a high standard deviation shows significant variability, which could be due to changes in weather patterns, irrigation practices, soil types, or crop management practices. Standard deviation helps in water resource planning and management, as regions with high variability may need more adaptive irrigation strategies. Understanding this measure aids in assessing the risk of water stress in crops, with higher variability indicating a greater risk, and provides insights into how climate change is affecting water use patterns, highlighting the need for robust drought mitigation strategies. Thus, analyzing the standard deviation of CWU is crucial for ensuring sustainable and efficient water use in agriculture.

4-2-1-Standard deviation of crop water use of tomato in Mediterranean Sea Basin

Figure 4-7 shows the map of standard deviation of crop water use of tomato in the Mediterranean Sea Basin.

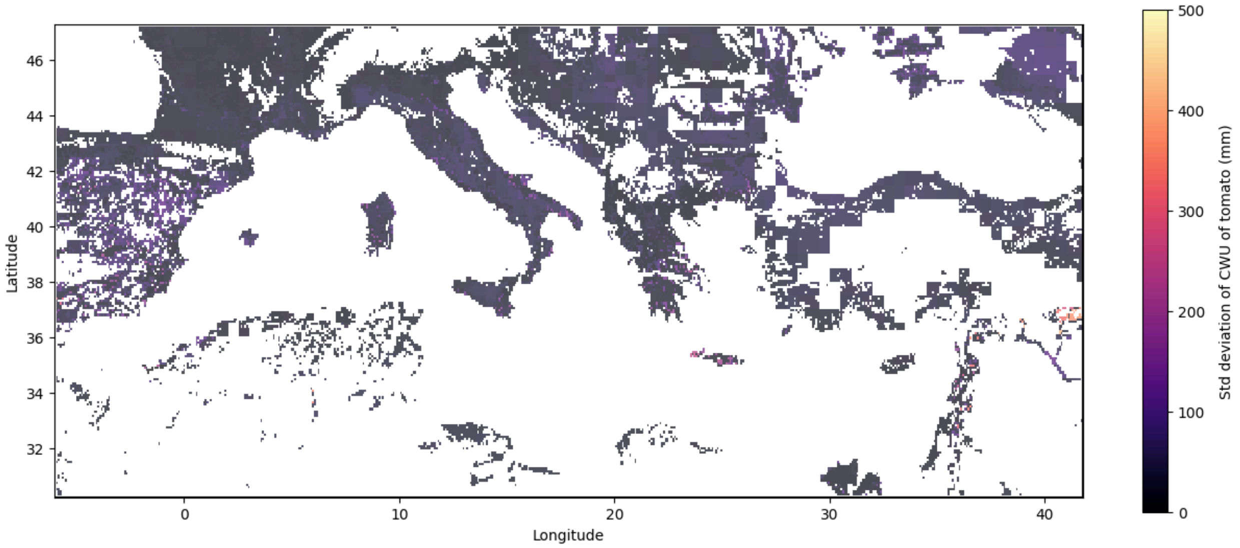


Figure 4-7- Std-deviation of crop water use of tomato in Mediterranean Sea Basin (1990-2019)

This map illustrates the standard deviation of crop water use (CWU) for tomatoes across the Mediterranean region. The map's color gradient, ranging from dark purple to bright yellow, represents varying levels of standard deviation in millimeters (mm), with darker colors indicating lower variability and lighter colors indicating higher variability. The highest variability areas, marked in bright yellow and orange, are scattered but prominently appear in specific locales, such as parts of Greece, Turkey, and small regions in Italy and Spain. These regions show standard deviations exceeding 200 mm, suggesting significant fluctuations in water use for tomato cultivation, potentially due to variable climatic conditions, irrigation practices, or soil types. Conversely, large areas with dark purple shading, particularly in France, Northern Italy, and parts of North Africa, exhibit lower standard deviations, generally below 50 mm, indicating more consistent water use for tomato crops.

4-2-2-Standard deviation of crop water use of tomato in Italy

Figure 4-8 shows the map of standard deviation of crop water use of tomato in Italy.

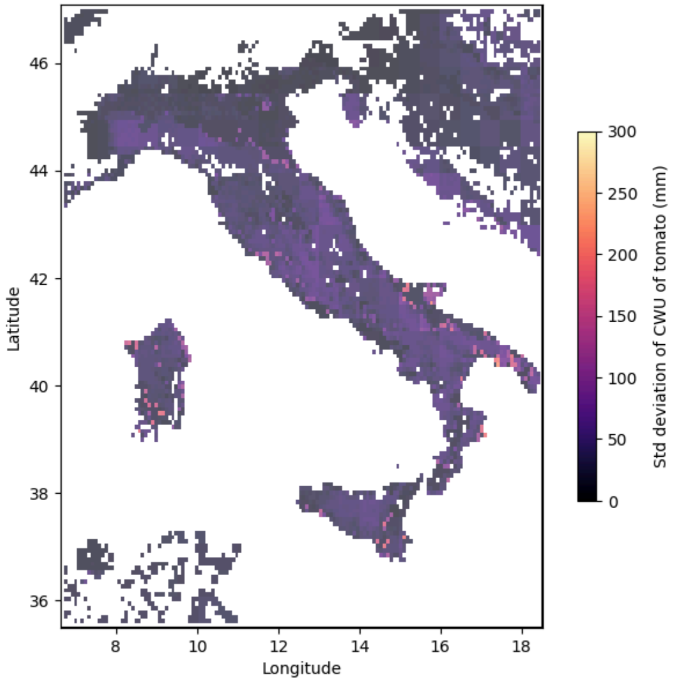


Figure 4-8- Std-deviation of crop water use of tomato in Italy (1990-2019)

This map presents the standard deviation of crop water use (CWU) for tomato cultivation across Italy, with values expressed in millimeters (mm). The color gradient from dark purple to bright yellow depicts areas of low to high variability in water use. Dark purple regions, primarily located in the northern part of the country, indicate a lower standard deviation, generally below 50 mm, suggesting stable and consistent water requirements for tomato crops in these areas. In contrast, the lighter shades of orange and yellow found in southern and central Italy, particularly in coastal regions and some inland areas, signify higher variability in water use, with standard deviations exceeding 200 mm in certain locales. These variations can be attributed to differing climatic conditions, irrigation practices, and soil characteristics across the country.

4-2-3-Standard deviation of crop water use of maize in Mediterranean Sea Basin

Figure 4-9 shows the map of standard deviation of crop water use of maize in the Mediterranean Sea Basin.

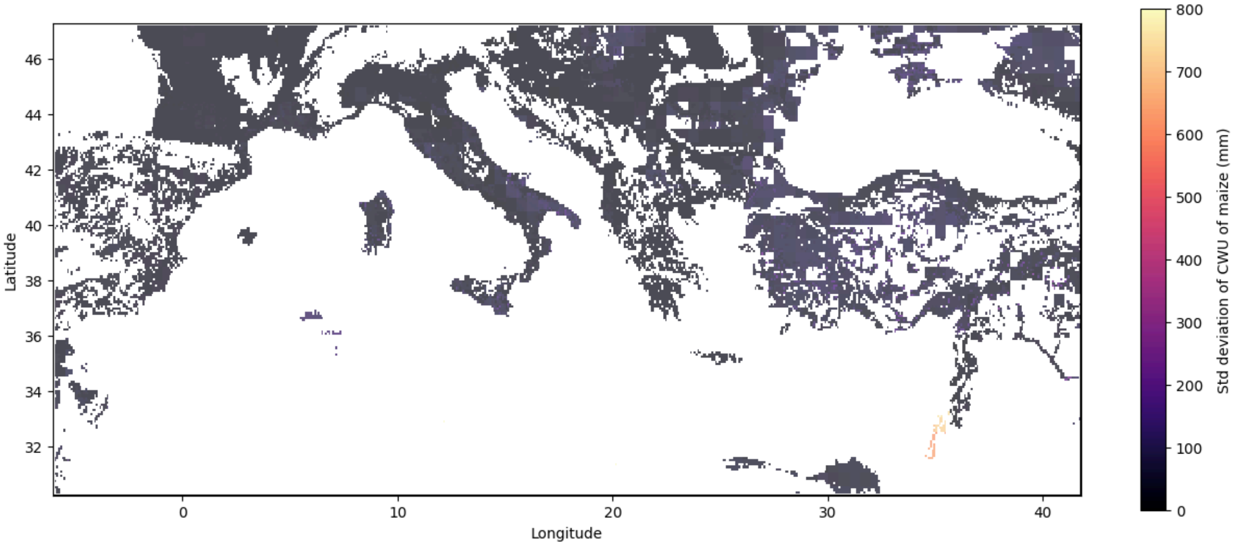


Figure 4-9- Std-deviation of crop water use of maize in Mediterranean Sea Basin (1990-2019)

This map illustrates the standard deviation of crop water use (CWU) for maize cultivation across the Mediterranean region, with measurements expressed in millimeters (mm). The color gradient, ranging from dark purple to bright yellow, represents areas of varying water use variability. Dark purple areas, primarily in northern Italy, southeastern France, and parts of Spain, indicate lower standard deviations, generally below 50 mm, suggesting consistent water use requirements for maize in these regions. In contrast, areas shaded in lighter hues of orange and yellow, particularly in Greece, Turkey, and some regions in Italy and North Africa, signify higher variability in water use, with standard deviations reaching up to 800 mm. This high variability can be attributed to diverse climatic conditions, differing irrigation practices, and varying soil properties across these regions.

4-2-4-Standard deviation of crop water use of maize in Italy

Figure 4-10 shows the map of standard deviation of crop water use of maize in Italy.

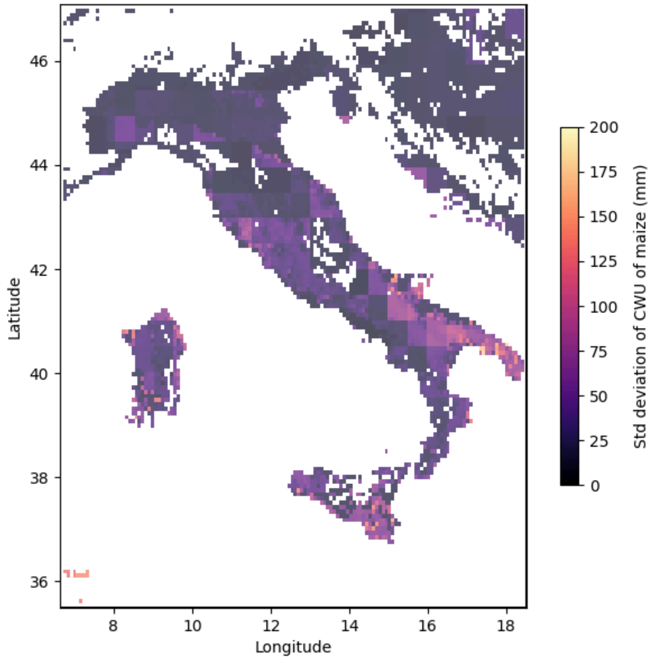


Figure 4-10- Std-deviation of crop water use of maize in Italy (1990-2019)

This map illustrates the standard deviation of crop water use (CWU) for maize cultivation across Italy, with the values expressed in millimeters (mm). The color gradient from dark purple to bright yellow indicates varying levels of water use variability, with darker colors representing lower standard deviations and lighter colors indicating higher variability.

Northern Italy, particularly the regions around the Po Valley, exhibits relatively low standard deviations, generally below 50 mm, as shown by the prevalence of dark purple areas. This suggests that maize water use in these regions is consistent, likely due to stable climatic conditions and well-established irrigation practices.

In contrast, central and southern Italy, including regions such as Puglia and parts of Sicily, display higher standard deviations, marked by lighter hues of orange and yellow. These areas have standard deviations that can reach up to 200 mm, indicating significant variability in water use. This variability can be attributed to the diverse microclimates, varying irrigation systems, and differing soil conditions found in these parts of Italy.

4-2-5-Standard deviation of crop water use of wheat in Mediterranean Sea Basin

Figure 4-11 shows the map of standard deviation of crop water use of wheat in the Mediterranean Sea Basin.

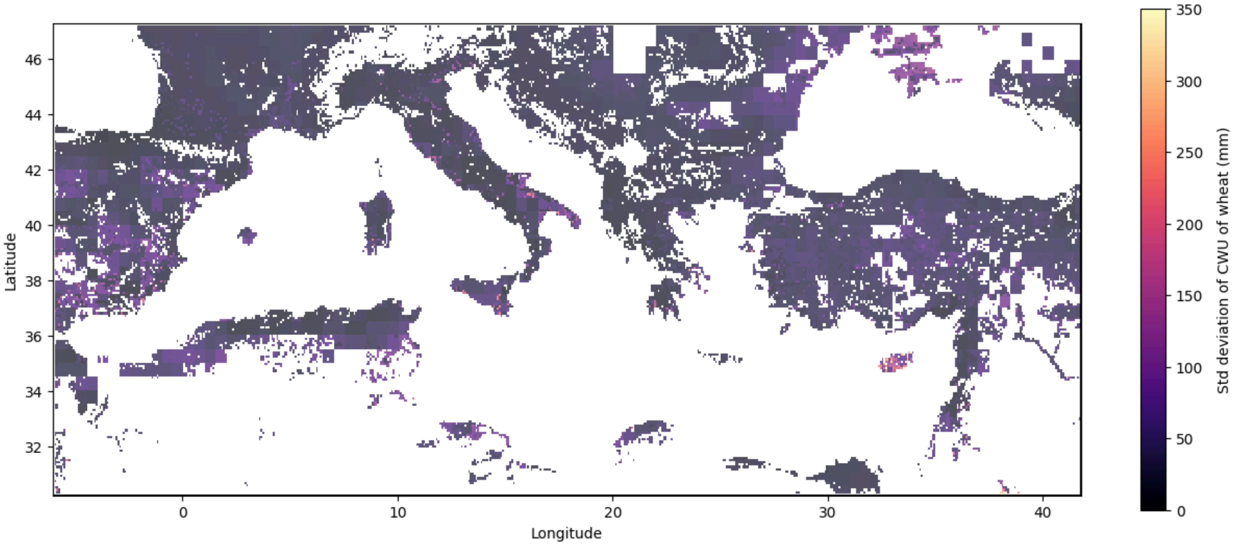


Figure 4-11- Std-deviation of crop water use of wheat in Mediterranean Sea Basin (1990-2019)

This map displays the standard deviation of crop water use (CWU) for wheat across Mediterranean countries, with values expressed in millimeters (mm). The color gradient, which ranges from dark purple to bright yellow, represents varying levels of water use variability.

Dark purple areas, predominantly located in Spain, Northern Italy, and parts of the Balkans, indicate lower standard deviations, generally below 50 mm, suggesting consistent water use for wheat cultivation in these regions. This consistency could be attributed to stable climatic conditions and uniform irrigation practices.

In contrast, regions shaded in lighter hues of orange and yellow, particularly in Cyprus, parts of Greece, southern Italy and the coastal regions of North Africa, exhibit higher variability in water use, with standard deviations reaching up to 350 mm. This high variability can be attributed to diverse climatic conditions, different irrigation practices, and varying soil properties across these areas.

The map reveals significant variability in the eastern Mediterranean, especially in regions of Turkey and parts of the Middle East, where wheat CWU shows standard deviations often exceeding 100 mm. This suggests that wheat farming in these areas faces considerable challenges in water management due to fluctuating environmental conditions.

4-2-6-Standard deviation of crop water use of wheat in Italy

Figure 4-12 shows the map of standard deviation of crop water use of wheat in Italy.

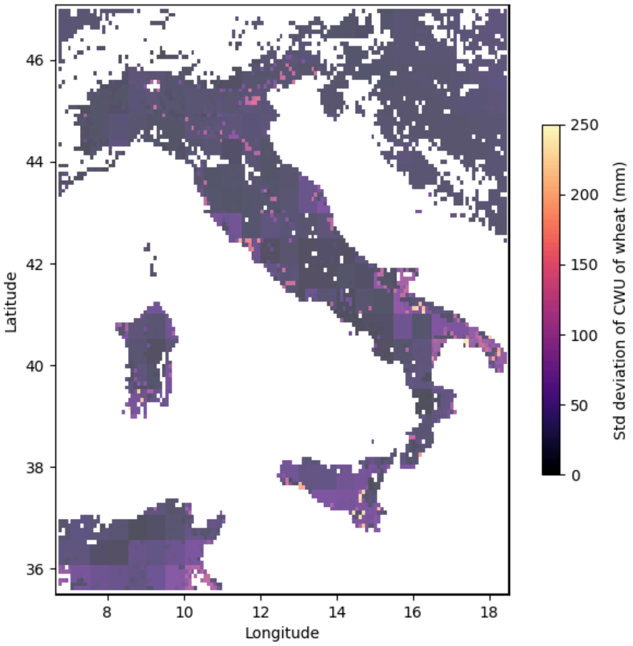


Figure 4-12- Std-deviation of crop water use of wheat in Italy (1990-2019)

This map illustrates the standard deviation of crop water use (CWU) for wheat cultivation across Italy, with measurements expressed in millimeters (mm). The color gradient, ranging from dark purple to bright yellow, represents varying levels of water use variability, with darker colors indicating lower standard deviations and lighter colors indicating higher variability.

Northern Italy, particularly the regions around the Po Valley, shows relatively low standard deviations, generally below 50 mm, as indicated by the prevalence of dark purple areas. This suggests that water use for wheat in these regions is consistent, likely due to stable climatic conditions and established irrigation practices.

Central and southern Italy, including regions such as Apulia, Calabria, and parts of Sicily, exhibit higher standard deviations, marked by lighter shades of orange and yellow. These areas have standard deviations reaching up to 250 mm, indicating significant variability in water use. This variability can be attributed to diverse climatic conditions, varying irrigation practices, and different soil properties found in these parts of Italy.

4-3- Coefficient of variation of crop water use

The coefficient of variation (CV) for crop water use quantifies the relative variability in water consumption among crops over a given period. It is computed as the ratio of the standard deviation (SD) of crop water use to the mean (average) crop water use, expressed as a percentage. A higher CV indicates greater variability in water requirements among crops relative to their average water use, while a lower CV suggests more consistent water use patterns. This measure is crucial for agricultural water management, aiding in the optimization of irrigation practices, accurate estimation of water demand, and efficient allocation of water resources to enhance crop yield and sustainability.

4-3-1- Coefficient of variation of crop water use of tomato in Mediterranean Sea Basin

Figure 4-13 shows the map of coefficient of variation of crop water use of tomato in the Mediterranean Sea Basin.

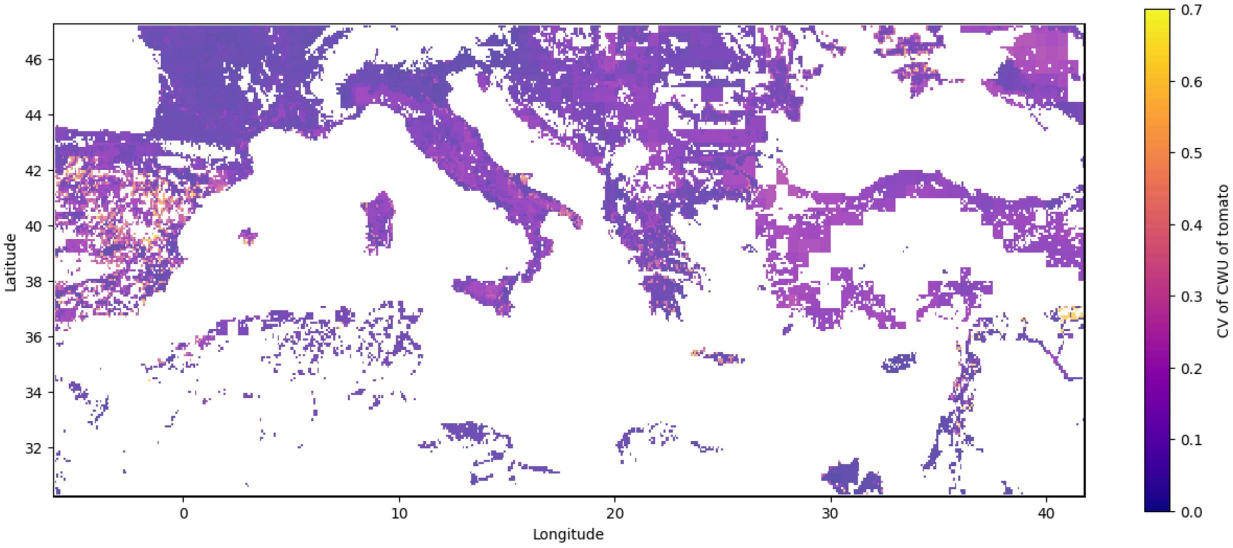


Figure 4-13- CV of crop water use of tomato in the Mediterranean Sea Basin (1990-2019)

This map illustrates the coefficient of variation (CV) of crop water use (CWU) for tomato cultivation across Mediterranean countries. The CV is a standardized measure of the dispersion of water use data points around the mean, expressed as a ratio. It is depicted here using a color gradient from dark purple to bright yellow, with darker colors indicating lower CV values and lighter colors indicating higher CV values.

Regions in Spain, northern Italy, and parts of Greece and Turkey exhibit relatively high CV values, marked by shades of orange and yellow, suggesting significant variability in water use for tomato crops in these areas. The CV values in these regions range from 0.4

to 0.7, indicating a high level of fluctuation relative to the mean water use. This variability may be due to diverse climatic conditions, soil properties, and irrigation practices within these regions.

Conversely, areas shaded in dark purple, such as parts of France, southern Italy, and the coastal regions of North Africa, show lower CV values, generally below 0.2. This indicates more consistent water use for tomato cultivation, likely due to stable environmental conditions and uniform agricultural practices.

4-3-2- Coefficient of variation of crop water use of tomato in Italy

Figure 4-14 shows the map of coefficient of variation of crop water use of tomato in Italy.

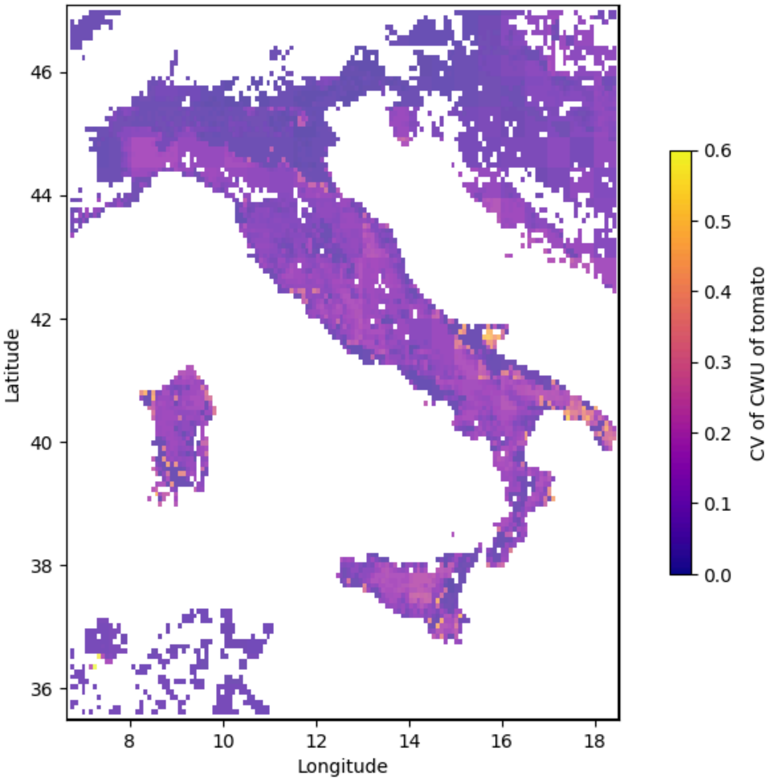


Figure 4-14- CV of crop water use of tomato in Italy (1990-2019)

This map depicts the coefficient of variation (CV) of crop water use (CWU) for tomato cultivation across Italy, with the CV values expressed as a ratio. The color gradient from dark purple to bright yellow represents varying levels of water use variability, with darker colors indicating lower CV values and lighter colors indicating higher CV values.

Northern Italy, particularly the regions around the Po Valley, shows relatively low CV values, generally below 0.2, as indicated by the prevalence of dark purple areas. This suggests consistent water use for tomato cultivation in these regions, likely due to stable climatic conditions and well-established irrigation practices.

In contrast, central and southern Italy, including regions such as Apulia, Calabria, and parts of Sicily, exhibit higher CV values, marked by lighter shades of orange and yellow. These areas have CV values reaching up to 0.6, indicating significant variability in water use. This variability can be attributed to diverse climatic conditions, varying irrigation practices, and different soil properties found in these parts of Italy.

4-3-3- Coefficient of variation of crop water use of maize in Mediterranean Sea Basin

Figure 4-15 shows the map of coefficient of variation of crop water use of maize in the Mediterranean Sea Basin.

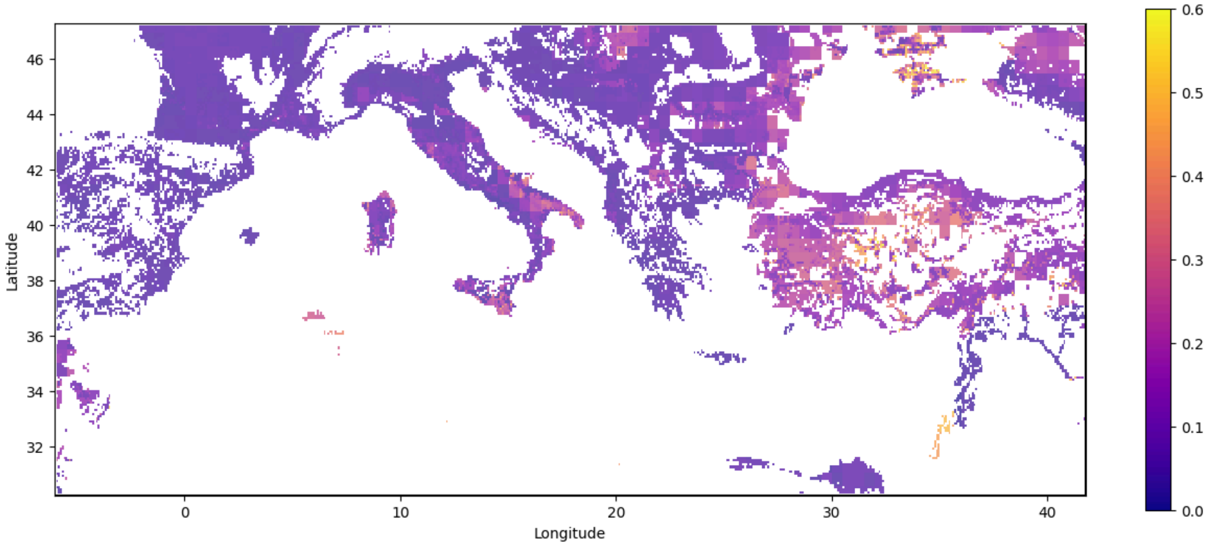


Figure 4-15- CV of crop water use of maize in the Mediterranean Sea Basin (1990-2019)

This map illustrates the coefficient of variation (CV) of crop water use (CWU) for maize cultivation across Mediterranean countries. The CV is a standardized measure of the dispersion of water use values around the mean, presented as a ratio. The color gradient, ranging from dark purple to bright yellow, represents varying levels of variability, with darker colors indicating lower CV values and lighter colors indicating higher CV values.

Regions in Spain, northern Italy, and parts of Greece and Turkey display relatively high CV values, marked by shades of orange and yellow. These areas have CV values up to 0.6, indicating significant variability in water use for maize. This high variability could be due to a combination of fluctuating climatic conditions, diverse soil properties, and inconsistent irrigation practices within these regions. In contrast, areas shaded in dark purple, such as parts of southern France, coastal regions of North Africa, and sections of Turkey, exhibit lower CV values, generally below 0.2.

4-3-4- Coefficient of variation of crop water use of maize in Italy

Figure 4-16 shows the map of coefficient of variation of crop water use of maize in Italy.

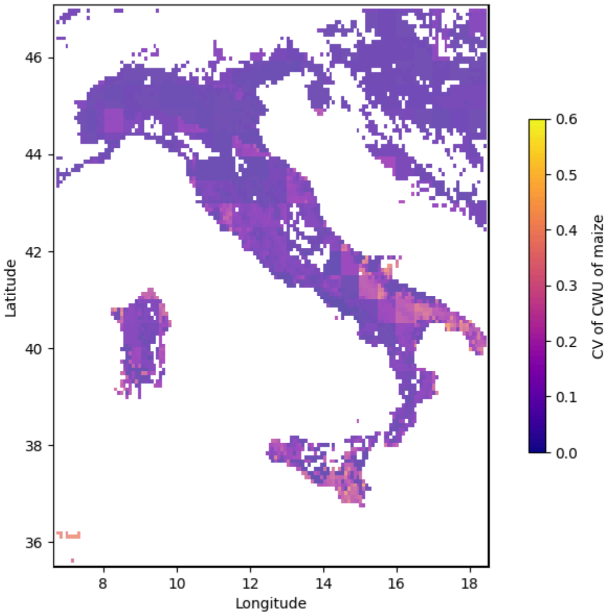


Figure 4-16- CV of crop water use of maize in Italy (1990-2019)

This map illustrates the coefficient of variation (CV) of crop water use (CWU) for maize cultivation across Italy, with CV values expressed as a ratio. The color gradient from dark purple to bright yellow indicates varying levels of water use variability, with darker colors representing lower CV values and lighter colors representing higher CV values.

Northern Italy, particularly the regions around the Po Valley, shows relatively low CV values, generally below 0.2, as indicated by the prevalence of dark purple areas. This suggests that water use for maize in these regions is consistent, likely due to stable climatic conditions and established irrigation practices. In contrast, central and southern Italy, including regions such as Apulia, Calabria, and parts of Sicily, exhibit higher CV values, marked by lighter shades of orange and yellow. These areas have CV values reaching up to 0.6, indicating significant variability in water use.

4-3-5- Coefficient of variation of crop water use of wheat in Mediterranean Sea Basin

Figure 4-17 shows the map of coefficient of variation of crop water use of wheat in the Mediterranean Sea Basin.

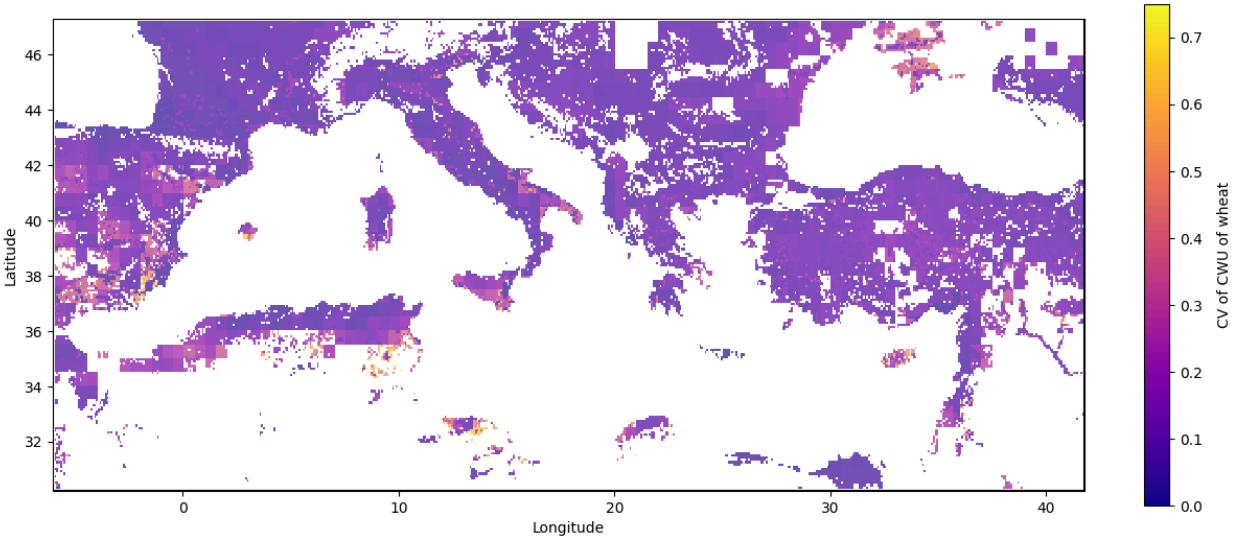


Figure 4-17- CV of crop water use of wheat in the Mediterranean Sea Basin (1990-2019)

This map presents the coefficient of variation (CV) of crop water use (CWU) for wheat cultivation across Mediterranean countries, with the CV values expressed as a ratio. The color gradient, ranging from dark purple to bright yellow, represents varying levels of variability in water use, with darker colors indicating lower CV values and lighter colors indicating higher CV values.

Regions in Spain, northern Italy, and parts of Greece and Turkey display relatively high CV values, marked by shades of orange and yellow. These areas exhibit CV values up to 0.75, indicating significant variability in water use for wheat. This high variability could be due to a combination of fluctuating climatic conditions, diverse soil properties, and inconsistent irrigation practices within these regions. In contrast, areas shaded in dark purple, such as parts of southern France, coastal regions of North Africa, and sections of Turkey, show lower CV values, generally below 0.2.

4-3-6- Coefficient of variation of crop water use of wheat in Italy

Figure 4-18 shows the map of coefficient of variation of crop water use of wheat in Italy.

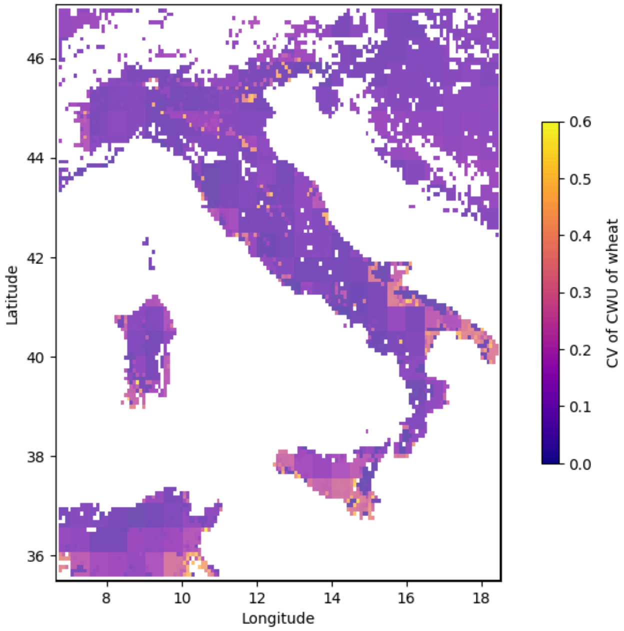


Figure 4-18- CV of crop water use of wheat in Italy (1990-2019)

This map illustrates the coefficient of variation (CV) of crop water use (CWU) for wheat cultivation across Italy, with CV values expressed as a ratio. The color gradient from dark purple to bright yellow represents varying levels of variability in water use, with darker colors indicating lower CV values and lighter colors indicating higher CV values.

Northern Italy, particularly the regions around the Po Valley, shows relatively low CV values, generally below 0.2, as indicated by the prevalence of dark purple areas. This suggests consistent water use for wheat in these regions, likely due to stable climatic conditions and well-established irrigation practices.

In contrast, central and southern Italy, including regions such as Apulia, Calabria, and parts of Sicily, exhibit higher CV values, marked by lighter shades of orange and yellow. These areas have CV values reaching up to 0.6, indicating significant variability in water use. This variability can be attributed to diverse climatic conditions, varying irrigation practices, and different soil properties found in these parts of Italy.

4-4- P-value of the trend

The p-value of a trend in crop water use versus years (1990-2019) indicates the statistical significance of the observed trend over that period. A p-value less than a chosen significance level (commonly 0.05) suggests that the trend is statistically significant, meaning the observed trend is unlikely to have occurred by random chance alone, and there is strong evidence to reject the null hypothesis of no trend. Conversely, a p-value greater than the significance level indicates that the trend is not statistically significant, implying the observed trend could be due to random variability. A significant positive trend indicates an increase in crop water use over the years, while a significant negative trend indicates a decrease. Understanding the p-value is crucial for assessing the real changes in crop water use and has important implications for agricultural practices, water resource management, and policy-making.

4-4-1-P-value of crop water use of tomato in Mediterranean Sea Basin

Figure 4-19 shows the map of p-values of crop water use of tomato in the Mediterranean Sea Basin.

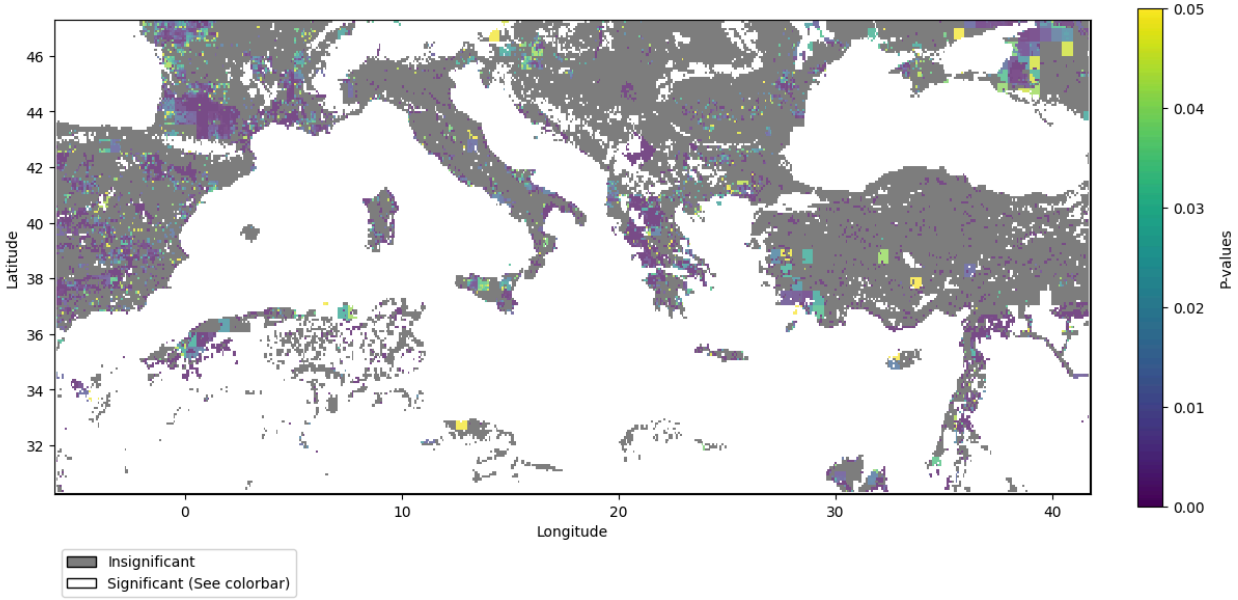


Figure 4-19- P-values of crop water use of tomato in the Mediterranean Sea Basin (1990-2019)

This map illustrates the p-values associated with the trend in crop water use (CWU) for tomato cultivation across Mediterranean countries from 1990 to 2019. The p-values are depicted using a color gradient, where shades from dark purple to bright yellow represent varying levels of statistical significance. Areas shaded in gray indicate regions where the trends are not statistically significant, with p-values greater than 0.05.

Regions with significant trends, marked in colors from dark green to yellow, have p-values less than or equal to 0.05, indicating that the observed trends in these areas are statistically significant and unlikely to have occurred by random chance alone. Notable regions with significant trends can be observed in parts of Spain, southern France, Italy, Greece, and Turkey, suggesting that these areas have experienced meaningful changes in tomato crop water use over the examined period.

The widespread presence of gray areas suggests that in many parts of the Mediterranean, trends in crop water use for tomatoes do not show significant changes, implying that the water use has been relatively stable or the changes are not statistically discernible. Conversely, the colored areas highlight regions where water use has either increased or decreased significantly, necessitating further investigation into the underlying causes, such as changes in climate, irrigation practices, or agricultural policies.

4-4-2-P-value of crop water use of tomato in Italy

Figure 4-20 shows the map of p-values of crop water use of tomato in Italy.

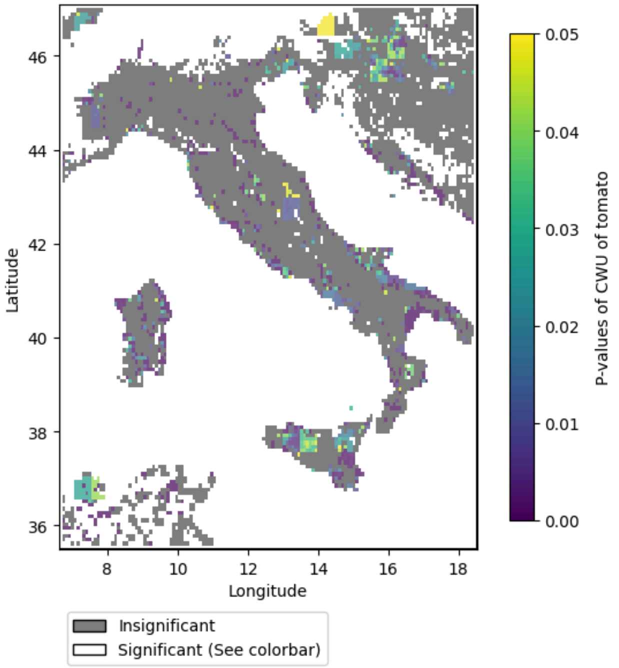


Figure 4-20 -P-values of crop water use of tomato in Italy (1990-2019)

This map illustrates the p-values associated with the trend in crop water use (CWU) for tomato cultivation across Italy from 1990 to 2019. The p-values are represented using a color gradient, with shades ranging from dark purple to bright yellow indicating different levels of statistical significance. Areas shaded in gray denote regions where the trends are not statistically significant, with p-values greater than 0.05.

Regions with significant trends, marked in colors from dark green to yellow, have p-values less than or equal to 0.05, indicating that the observed trends in these areas are statistically significant and unlikely to be due to random chance. Notable regions with significant trends can be observed in parts of northern Italy, including the Po Valley, and some areas in southern Italy and Sicily. These significant trends suggest meaningful changes in tomato crop water use over the examined period in these regions.

4-4-3-P-value of crop water use of maize in Mediterranean Sea Basin

Figure 4-21 shows the map of p-values of crop water use of maize in the Mediterranean Sea Basin.

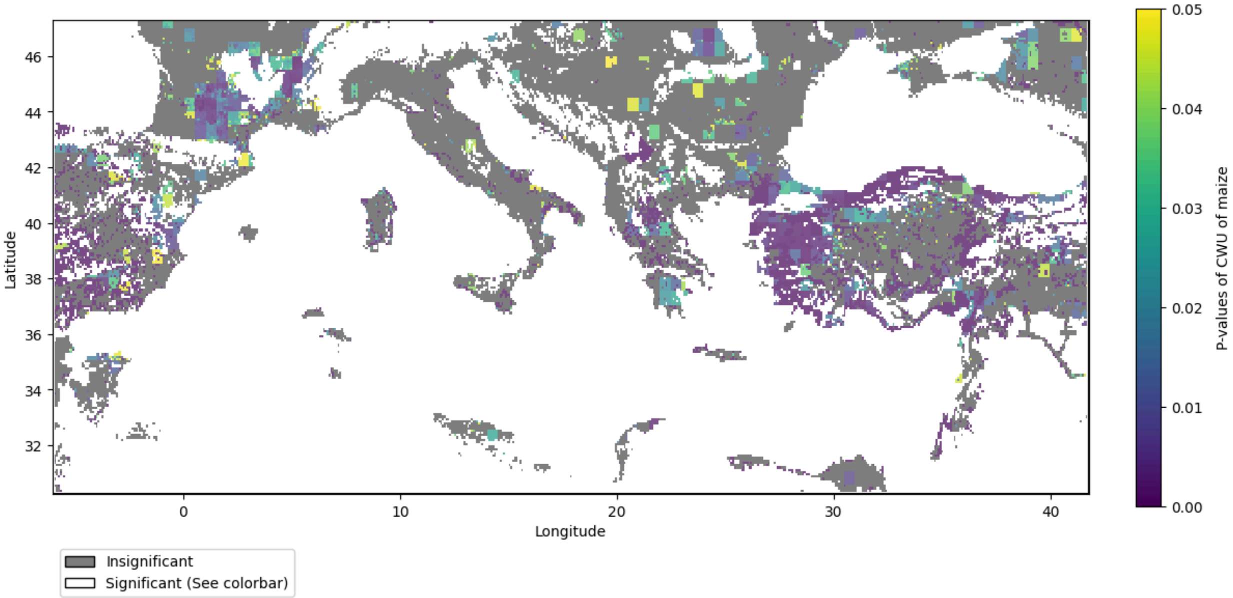


Figure 4-21- P-values of crop water use of maize in the Mediterranean Sea Basin (1990-2019)

This map illustrates the p-values associated with the trend in crop water use (CWU) for maize cultivation across Mediterranean countries from 1990 to 2019. The p-values are displayed using a color gradient, with shades from dark purple to bright yellow indicating different levels of statistical significance. Areas shaded in gray represent regions where the trends are not statistically significant, with p-values greater than 0.05.

Regions with significant trends, marked in colors from yellow to dark green, have p-values less than or equal to 0.05, indicating that the observed trends in these areas are statistically significant and unlikely to have occurred by random chance.The dark purple areas, representing the lowest p-values (close to 0), indicate regions where the trends are highly significant. Significant trends can be observed in parts of Spain, southern France, northern Italy, Greece, and Turkey, suggesting that these areas have experienced meaningful changes in maize crop water use over the examined period.

4-4-4-P-value of crop water use of maize in Italy

Figure 4-22 shows the map of p-values of crop water use of maize in Italy.

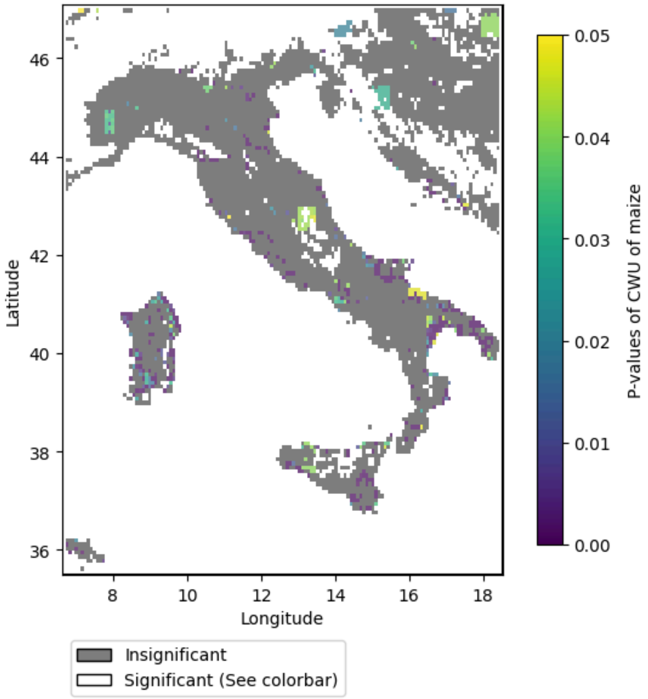


Figure 4-22 -P-values of crop water use of maize in Italy (1990-2019)

This map depicts the p-values associated with trends in crop water use (CWU) for maize across Italy from 1990 to 2019. The color gradient, ranging from dark purple to bright yellow, represents varying degrees of statistical significance. Areas shaded in gray indicate regions where the trends are not statistically significant, with p-values greater than 0.05, suggesting no strong evidence of a trend in maize CWU changes over the period.

In regions highlighted with darker shades of purple, indicating p-values close to zero, there is very strong statistical evidence to suggest significant changes in crop water use for maize. These regions, primarily located in northern Italy, reflect robust trends in CWU, likely due to factors such as shifts in agricultural practices, irrigation technology, or climatic influences.

The few areas colored in yellow and green represent regions with p-values between 0.01 and 0.05, denoting statistically significant trends, albeit with less confidence than the darker purple areas. These regions might have experienced moderate changes in water use that are statistically detectable and may require targeted investigations to understand the underlying causes.

4-4-5-P-value of crop water use of wheat in Mediterranean Sea Basin

Figure 4-23 shows the map of p-values of crop water use of wheat in the Mediterranean Sea Basin.

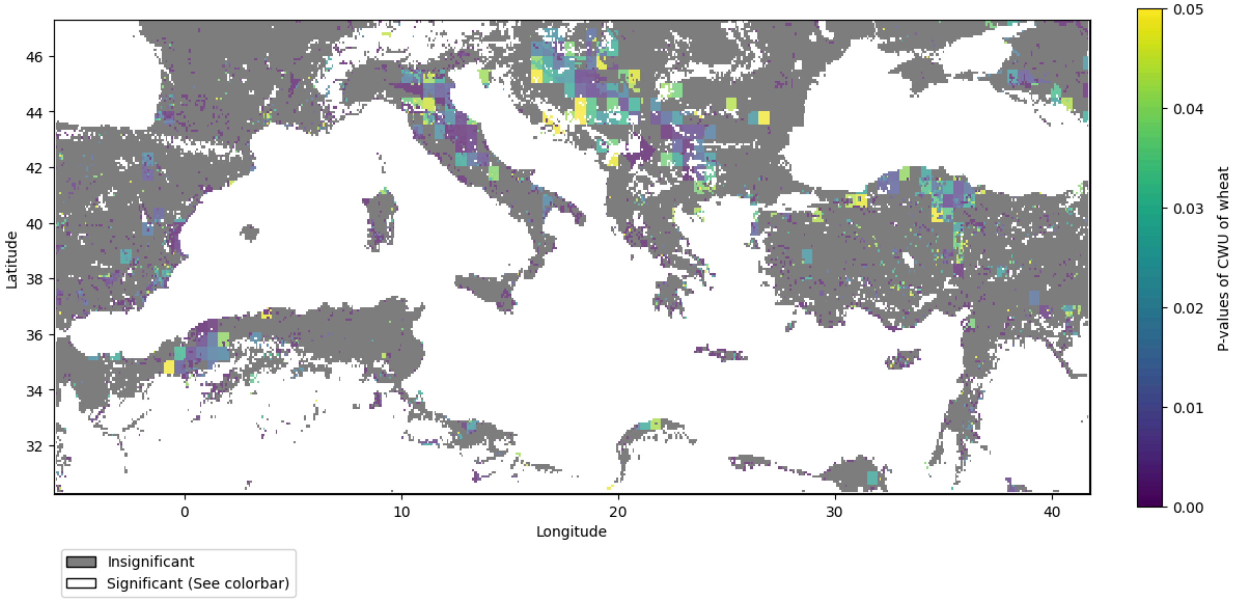


Figure 4-23- P-values of crop water use of wheat in the Mediterranean Sea Basin (1990-2019)

This map illustrates the p-values associated with trends in crop water use (CWU) for wheat cultivation across Mediterranean countries from 1990 to 2019. The p-values are displayed using a color gradient, with dark purple indicating the lowest p-values (close to 0), transitioning to bright yellow for higher p-values (up to 0.05). Gray areas represent regions where the trends are not statistically significant, with p-values greater than 0.05.

Regions with significant trends, highlighted in colors from yellow to dark green, have p-values less than or equal to 0.05, suggesting that the observed trends in these areas are statistically significant and unlikely to have occurred by random chance. Significant trends can be observed in parts of Spain, southern France, northern Italy, the Balkans, and Turkey, indicating meaningful changes in wheat crop water use over the examined period.

The dark purple areas, representing the lowest p-values, indicate regions with the most statistically significant trends. These areas demonstrate strong evidence of changes in wheat crop water use, which may be attributed to factors such as shifts in climatic conditions, agricultural practices, or irrigation technologies. Notable dark purple regions can be seen in parts of northern Italy and the Balkans, where the trends in water use have been particularly pronounced.

4-4-6-P-value of crop water use of wheat in Italy

Figure 4-24 shows the map of p-values of crop water use of wheat in Italy.

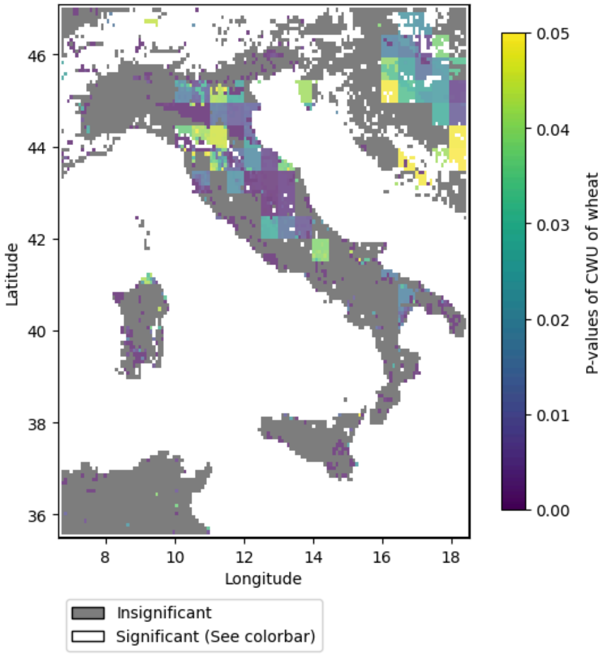


Figure 4-24 -P-values of crop water use of wheat in Italy (1990-2019)

This map illustrates the p-values associated with trends in crop water use (CWU) for wheat cultivation across Italy from 1990 to 2019. The p-values are displayed using a color gradient, with dark purple indicating the lowest p-values (close to 0) and bright yellow indicating higher p-values (up to 0.05). Areas shaded in gray represent regions where the trends are not statistically significant, with p-values greater than 0.05.

Regions with significant trends, highlighted in colors from yellow to dark green, have p-values less than or equal to 0.05, suggesting that the observed trends in these areas are statistically significant and unlikely to have occurred by random chance.The dark purple areas, representing the lowest p-values, indicate regions with the most statistically significant trends. Significant trends can be observed in parts of northern Italy, particularly around the Po Valley, as well as in some areas of central and southern Italy. These regions indicate meaningful changes in wheat crop water use over the examined period.

4-5- Slope of the trend

The slope of a trend of crop water use (measured in millimeters, mm) over time (measured in years) indicates the rate at which water use by crops is changing annually. A positive slope signifies an increase in crop water use, potentially due to factors like higher temperatures, expanded irrigation, changes to water-intensive crops, or agricultural practices that demand more water. Conversely, a negative slope indicates a decrease in water use, possibly due to improved irrigation efficiency, adoption of less water-intensive crops, reduced agricultural activity, or climatic shifts reducing water needs. A zero slope suggests stable water use, reflecting consistent climatic conditions and agricultural practices.

4-5-1-Slope of crop water use of tomato in Mediterranean Sea Basin

Figure 4-25 shows the map of slope values(mm/year) of crop water use of tomato in the Mediterranean Sea Basin.

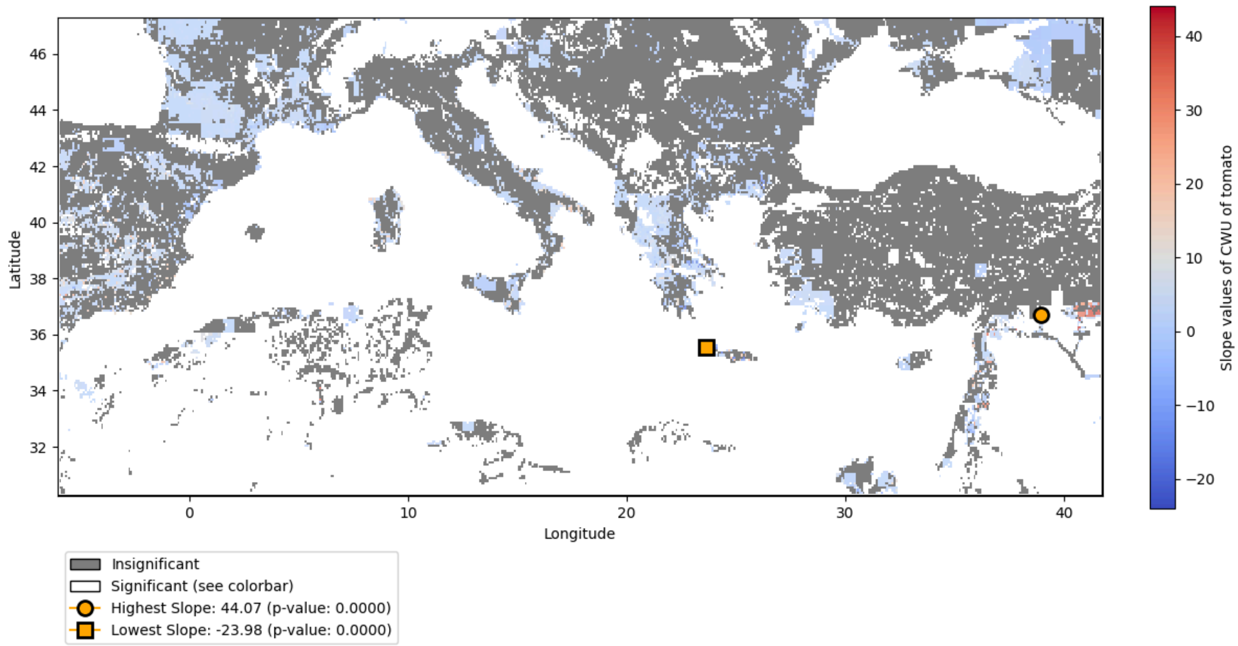


Figure 4-25- Slope values of crop water use of tomato in the Mediterranean Sea Basin (1990-2019)

This map illustrates the slope values associated with the trend in crop water use (CWU) for tomato cultivation across Mediterranean countries from 1990 to 2019. The slope values, expressed in millimeters per year, are displayed using a color gradient ranging from dark blue to dark red. Dark blue indicates negative slopes (decreasing trends), while dark red indicates positive slopes (increasing trends). Areas shaded in gray represent regions where the trends are not statistically significant.

The highest slope value, marked with an orange circle, is located in Syria, showing an increase in CWU for tomatoes by 44.07 mm per year with a p-value of 0.0000, indicating a highly significant upward trend. Conversely, the lowest slope value, marked with an orange square, is located in southeastern Greece (Island of Crete), indicating a decrease in CWU for tomatoes by -23.98 mm per year, also with a p-value of 0.0000, reflecting a highly significant downward trend.

Regions with statistically significant trends are depicted in various shades of blue and red, suggesting notable changes in tomato water use over the examined period. These significant areas are spread across the Mediterranean, with some regions experiencing increases in water use (positive slopes) and others experiencing decreases (negative slopes).

4-5-1-1-Highest and lowest slope

Figure 4-26 shows the graph of crop water use of tomato(mm) versus time(year) with the highest and lowest slope in the Mediterranean Sea Basin.

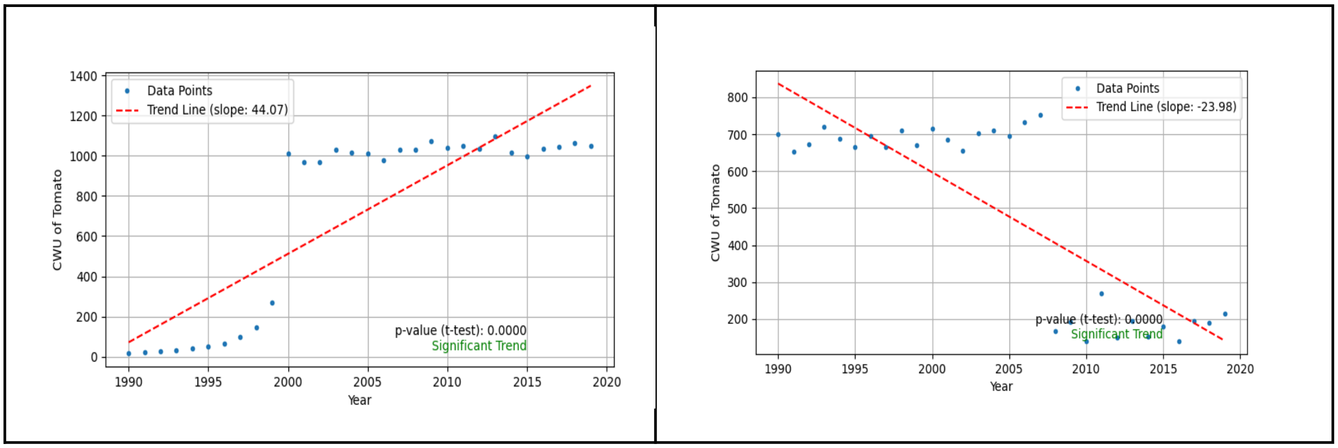


Figure 4-26- Trends with the highest and lowest slope for tomato in the Mediterranean Sea Basin

The trend shown in these graphs illustrates the crop water use (CWU) of tomato cultivation over the years from 1990 to 2019. The data points (blue dots) represent the actual annual CWU values, while the red dashed line indicates the linear trend line fitted to these points.

The highest slope of the trend line is 44.07, meaning that, on average, the CWU for tomatoes increased by 44.07 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant.

This very low p-value suggests that the observed increasing trend is highly unlikely to be due to random chance, confirming a significant upward trend in the water use for tomato cultivation over these years in Syria.

The lowest slope of the trend line is -23.98, meaning that, on average, the CWU for tomatoes decreased by 23.98 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed decreasing trend is highly unlikely to be due to random chance, confirming a significant downward trend in the water use for tomato cultivation over these years in Greece.

Overall, the graph clearly shows that the water use for tomatoes has been increasing with the highest slope and decreasing with the lowest slope, significantly from 1990 to 2019, necessitating further analysis into the causes and potential measures to manage this increasing water demand effectively.

4-5-2-Slope of crop water use of tomato in Italy

Figure 4-27 shows the map of slope values(mm/year) of crop water use of tomato in Italy.

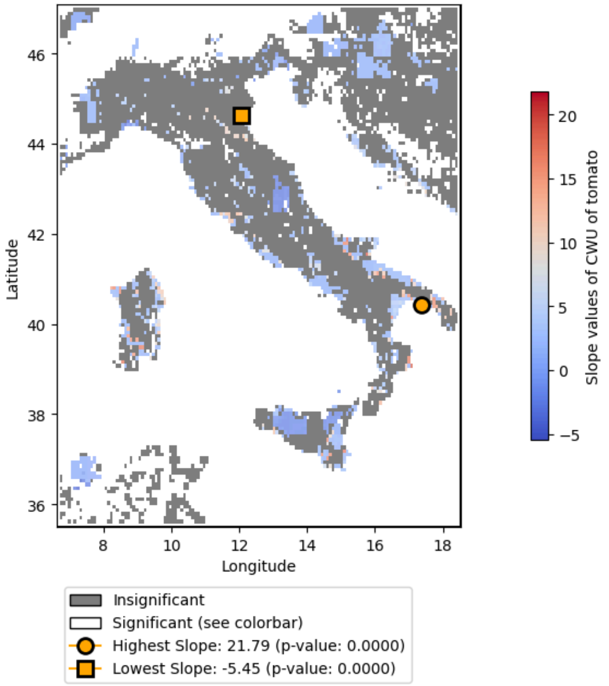


Figure 4-27- Slope values of crop water use of tomato in Italy (1990-2019)

This map illustrates the slope values associated with the trend in crop water use (CWU) for tomato cultivation across Italy from 1990 to 2019. The slope values, expressed in millimeters per year, are shown using a color gradient ranging from dark blue to dark red. Dark blue indicates negative slopes (decreasing trends), while dark red indicates positive slopes (increasing trends). Areas shaded in gray represent regions where the trends are not statistically significant.

The highest slope value, marked with an orange circle, is located in southeastern Italy (Puglia), showing an increase in CWU for tomatoes by 21.79 mm per year with a p-value of 0.0000, indicating a highly significant upward trend. Conversely, the lowest slope value, marked with an orange square, is located in northern Italy (Emilia-Romagna), indicating a decrease in CWU for tomatoes by -5.45 mm per year, also with a p-value of 0.0000, reflecting a highly significant downward trend.

Regions with statistically significant trends are depicted in various shades of blue and red, suggesting notable changes in tomato water use over the examined period. These significant areas are spread across Italy, with some regions experiencing increases in water use (positive slopes) and others experiencing decreases (negative slopes). The changes in CWU could be attributed to various factors, including shifts in climatic conditions, agricultural practices, and irrigation methods.

4-5-2-1-Highest and lowest slope

Figure 4-28 shows the graph of crop water use of tomato(mm) versus time(year) with the highest and lowest slope in Italy.

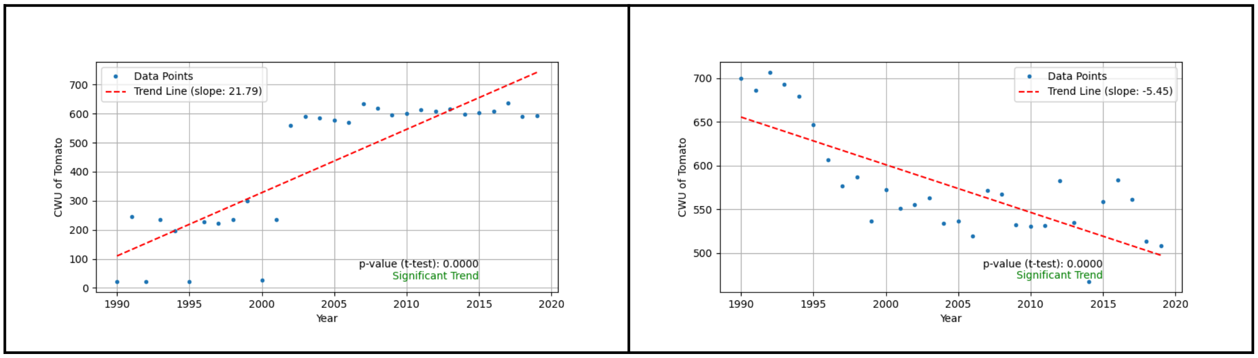


Figure 4-28- Trends with the highest and lowest slope for tomato in Italy

The highest slope of the trend line is 21.79, meaning that, on average, the CWU for tomatoes increased by 21.79 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed increasing trend is highly unlikely to be due to random chance, confirming a significant upward trend in the water use for tomato cultivation in Italy (Puglia) over these years.

The lowest slope of the trend line is -5.45, meaning that, on average, the CWU for tomatoes decreased by 5.45 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed decreasing trend is highly unlikely to be due to random chance, confirming a significant downward trend in the water use for tomato cultivation in Italy (Emilia-Romagna) over these years.

4-5-3-Slope of crop water use of maize in Mediterranean Sea Basin

Figure 4-29 shows the map of slope values(mm/year) of crop water use of maize in the Mediterranean Sea Basin.

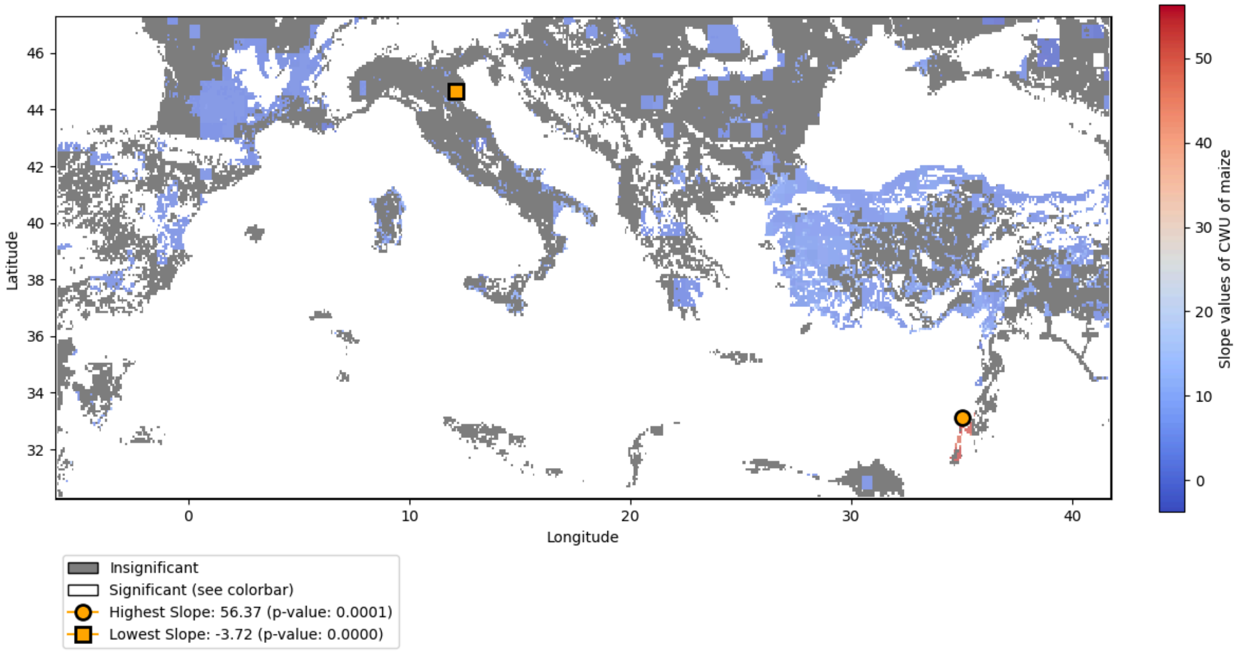


Figure 4-29- Slope values of crop water use of maize in the Mediterranean Sea Basin (1990-2019)

This map illustrates the slope values associated with the trend in crop water use (CWU) for maize cultivation across Mediterranean countries from 1990 to 2019. The slope values, expressed in millimeters per year, are shown using a color gradient ranging from dark blue to dark red. Dark blue indicates negative slopes (decreasing trends), while dark red indicates positive slopes (increasing trends). Areas shaded in gray represent regions where the trends are not statistically significant.

The highest slope value, marked with an orange circle, is located in the southern part of Lebanon, showing an increase in CWU for maize by 56.37 mm per year with a p-value of 0.0001, indicating a highly significant upward trend. Conversely, the lowest slope value, marked with an orange square, is located in northern Italy, indicating a decrease in CWU for maize by -3.72 mm per year, also with a p-value of 0.0000, reflecting a highly significant downward trend.

Regions with statistically significant trends are depicted in various shades of blue and red, suggesting notable changes in maize water use over the examined period. These significant areas are spread across the Mediterranean, with some regions experiencing increases in water use (positive slopes) and others experiencing decreases (negative slopes).

4-5-3-1-Highest and lowest slope

Figure 4-30 shows the graph of crop water use of maize(mm) versus time(year) with the highest and lowest slope in the Mediterranean Sea Basin.

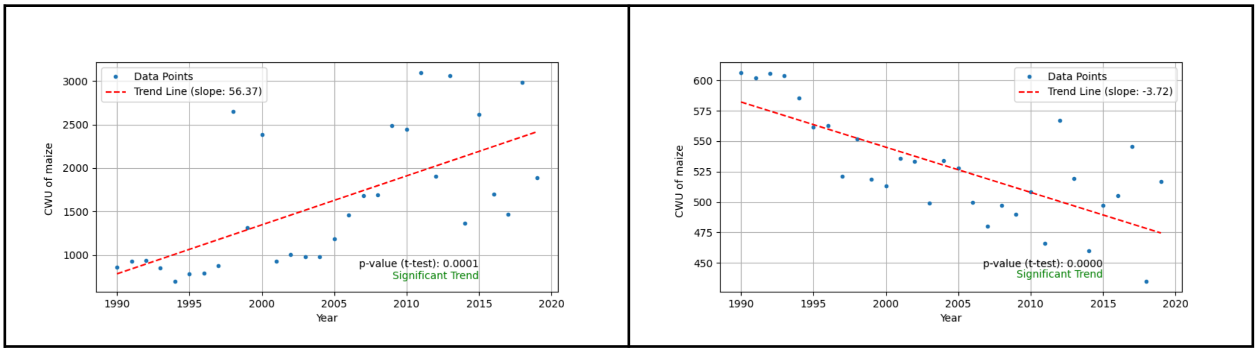


Figure 4-30- Trends with the highest and lowest slope for maize in the Mediterranean Sea Basin

The highest slope of the trend line is 56.37, meaning that, on average, the CWU for maize increased by 56.37 millimeters per year over the observed period. The p-value associated with this trend is 0.0001, indicating that the trend is statistically significant. This very low p-value suggests that the observed increasing trend is highly unlikely to be due to random chance, confirming a significant upward trend in the water use for maize cultivation over these years in Lebanon.

The lowest slope of the trend line is -3.72, meaning that, on average, the CWU for maize decreased by 3.72 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed decreasing trend is highly unlikely to be due to random chance, confirming a significant downward trend in the water use for maize cultivation over these years in Italy.

4-5-4-Slope of crop water use of maize in Italy

Figure 4-31 shows the map of slope values(mm/year) of crop water use of maize in Italy.

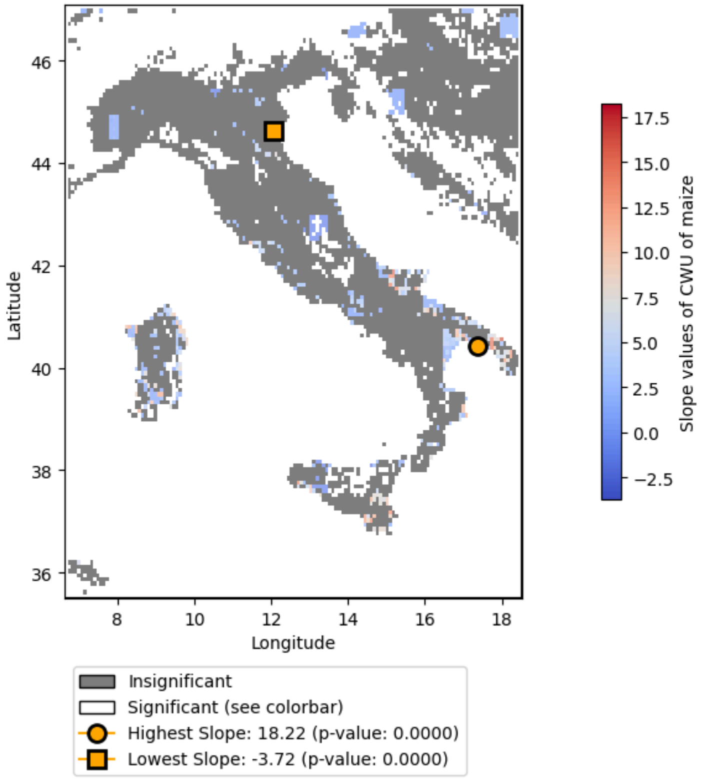


Figure 4-31- Slope values of crop water use of maize in Italy (1990-2019)

This map illustrates the slope values associated with the trend in crop water use (CWU) for maize cultivation across Italy from 1990 to 2019. The slope values, expressed in millimeters per year, are depicted using a color gradient ranging from dark blue to dark red. Dark blue indicates negative slopes (decreasing trends), while dark red indicates positive slopes (increasing trends). Areas shaded in gray represent regions where the trends are not statistically significant.

The highest slope value, marked with an orange circle, is located in southeastern Italy (Puglia), showing an increase in CWU for maize by 18.22 mm per year with a p-value of 0.0000, indicating a highly significant upward trend. Conversely, the lowest slope value, marked with an orange square, is located in northern Italy (Emilia-Romagna), indicating a decrease in CWU for maize by -3.72 mm per year, also with a p-value of 0.0000, reflecting a highly significant downward trend.

Regions with statistically significant trends are depicted in various shades of blue and red, suggesting notable changes in maize water use over the examined period. These significant areas are spread across Italy, with some regions experiencing increases in water use (positive slopes) and others experiencing decreases (negative slopes). The changes in CWU could be attributed to various factors, including shifts in climatic conditions, agricultural practices, and irrigation methods.

4-5-4-1-Highest and lowest slope

Figure 4-32 shows the graph of crop water use of maize (mm) versus time(year) with the highest and lowest slope in Italy.

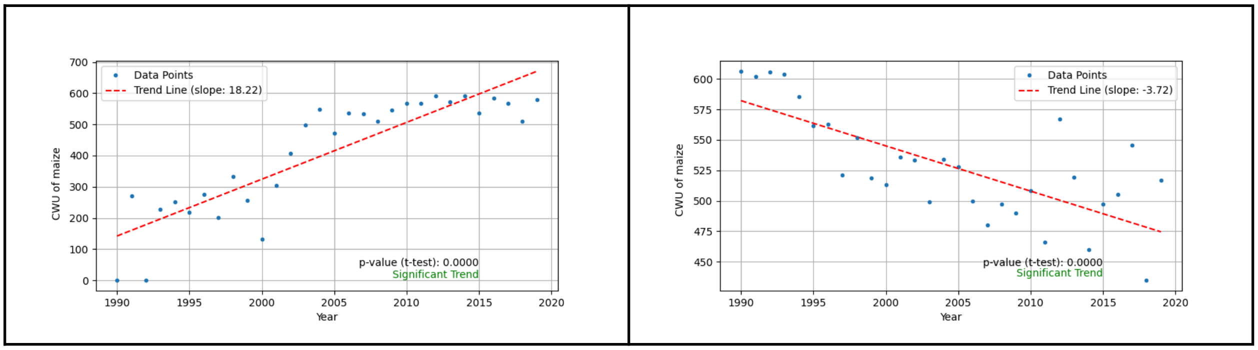


Figure 4-32- Trends with the highest and lowest slope for maize in Italy

The highest slope of the trend line is 18.22, meaning that, on average, the CWU for maize increased by 18.22 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed increasing trend is highly unlikely to be due to random chance, confirming a significant upward trend in the water use for maize cultivation in Italy (Puglia) over these years.

The lowest slope of the trend line is -3.72, meaning that, on average, the CWU for maize decreased by 3.72 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed decreasing trend is highly unlikely to be due to random chance, confirming a significant downward trend in the water use for maize cultivation in Italy (Emilia-Romagna) over these years.

4-5-5-Slope of crop water use of wheat in Mediterranean Sea Basin

Figure 4-33 shows the map of slope values(mm/year) of crop water use of wheat in the Mediterranean Sea Basin.

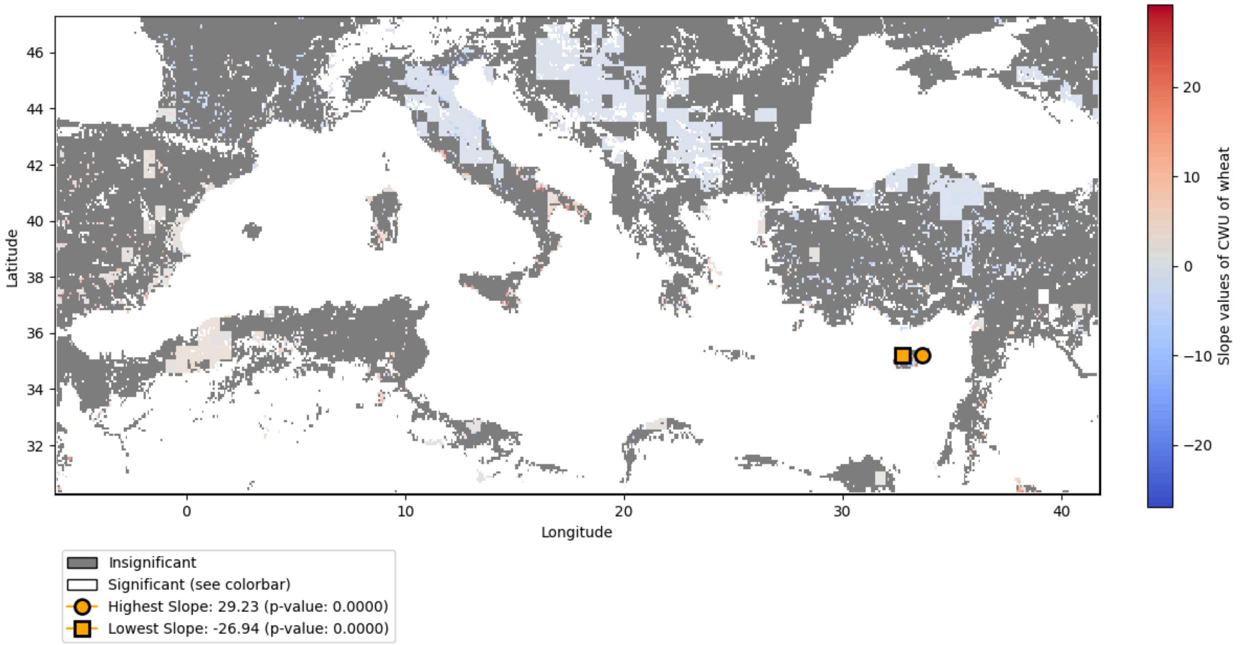


Figure 4-33- Slope values of crop water use of wheat in the Mediterranean Sea Basin (1990-2019)

This map illustrates the slope values associated with the trend in crop water use (CWU) for wheat cultivation across Mediterranean countries from 1990 to 2019. The slope values, expressed in millimeters per year, are depicted using a color gradient ranging from dark blue to dark red. Dark blue indicates negative slopes (decreasing trends), while dark red indicates positive slopes (increasing trends). Areas shaded in gray represent regions where the trends are not statistically significant.

The highest slope value, marked with an orange circle, is located in Cyprus, showing an increase in CWU for wheat by 29.23 mm per year with a p-value of 0.0000, indicating a highly significant upward trend. Conversely, the lowest slope value, marked with an orange square, is also located in Cyprus, indicating a decrease in CWU for wheat by -26.94 mm per year, also with a p-value of 0.0000, reflecting a highly significant downward trend.

Regions with statistically significant trends are depicted in various shades of blue and red, suggesting notable changes in wheat water use over the examined period. These significant areas are spread across the Mediterranean, with some regions experiencing increases in water use (positive slopes) and others experiencing decreases (negative slopes). The changes in CWU could be attributed to various factors, including shifts in climatic conditions, agricultural practices, and irrigation methods.

4-5-5-1-Highest and lowest slope

Figure 4-34 shows the graph of crop water use of wheat(mm) versus time(year) with the highest and lowest slope in the Mediterranean Sea Basin.

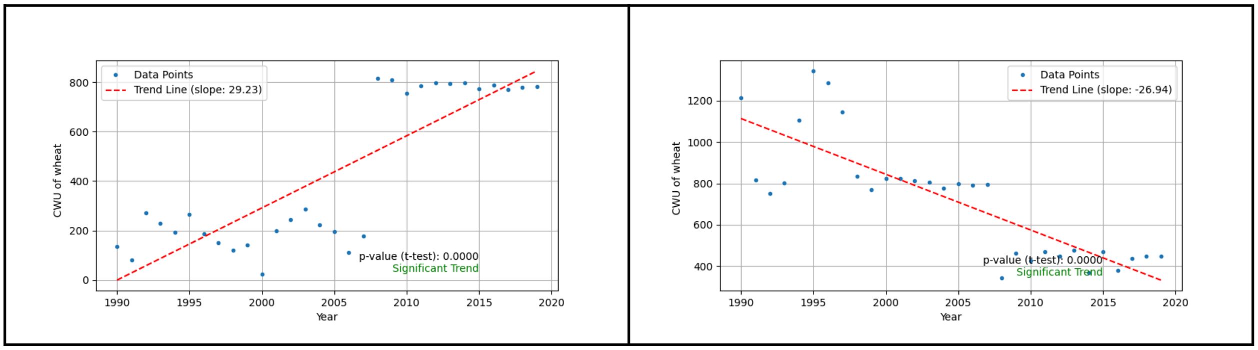


Figure 4-34- Trends with the highest and lowest slope for wheat in the Mediterranean Sea Basin

The highest slope of the trend line is 29.23, meaning that, on average, the CWU for wheat increased by 29.23 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed increasing trend is highly unlikely to be due to random chance, confirming a significant upward trend in the water use for wheat cultivation over these years in Cyprus.

The lowest slope of the trend line is -26.94, meaning that, on average, the CWU for wheat decreased by 26.94 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed decreasing trend is highly unlikely to be due to random chance, confirming a significant downward trend in the water use for wheat cultivation over these years in Cyprus.

4-5-6-Slope of crop water use of wheat in Italy

Figure 4-35 shows the map of slope values(mm/year) of crop water use of wheat in Italy.

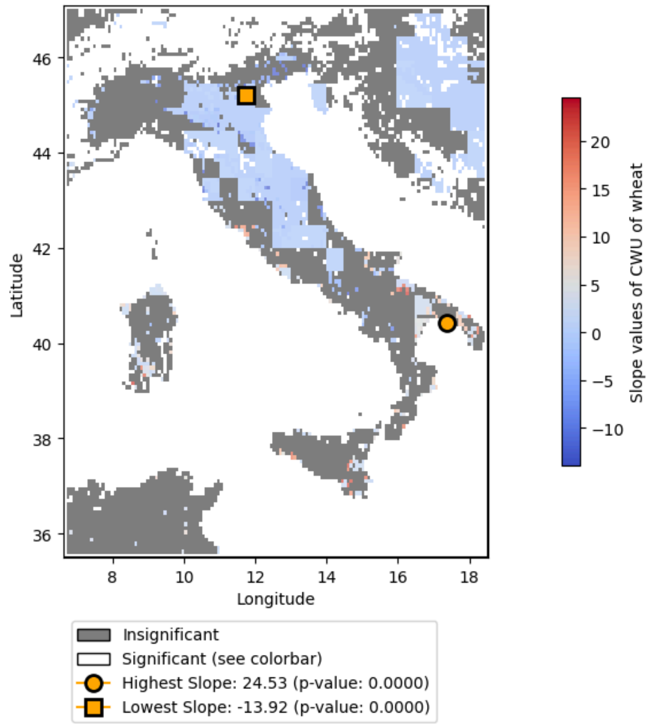


Figure 4-35- Slope values of crop water use of wheat in Italy (1990-2019)

This map illustrates the slope values associated with the trend in crop water use (CWU) for wheat cultivation across Italy from 1990 to 2019. The slope values, expressed in millimeters per year, are depicted using a color gradient ranging from dark blue to dark red. Dark blue indicates negative slopes (decreasing trends), while dark red indicates positive slopes (increasing trends). Areas shaded in gray represent regions where the trends are not statistically significant.

The highest slope value, marked with an orange circle, is located in southeastern Italy, showing an increase in CWU for wheat by 24.53 mm per year with a p-value of 0.0000, indicating a highly significant upward trend. Conversely, the lowest slope value, marked with an orange square, is located in northern Italy, indicating a decrease in CWU for wheat by -13.92 mm per year, also with a p-value of 0.0000, reflecting a highly significant downward trend.

Regions with statistically significant trends are depicted in various shades of blue and red, suggesting notable changes in wheat water use over the examined period. These significant areas are spread across Italy, with some regions experiencing increases in water use (positive slopes) and others experiencing decreases (negative slopes).

4-5-6-1-Highest and lowest slope

Figure 4-36 shows the graph of crop water use of wheat (mm) versus time(year) with the highest and lowest slope in Italy.

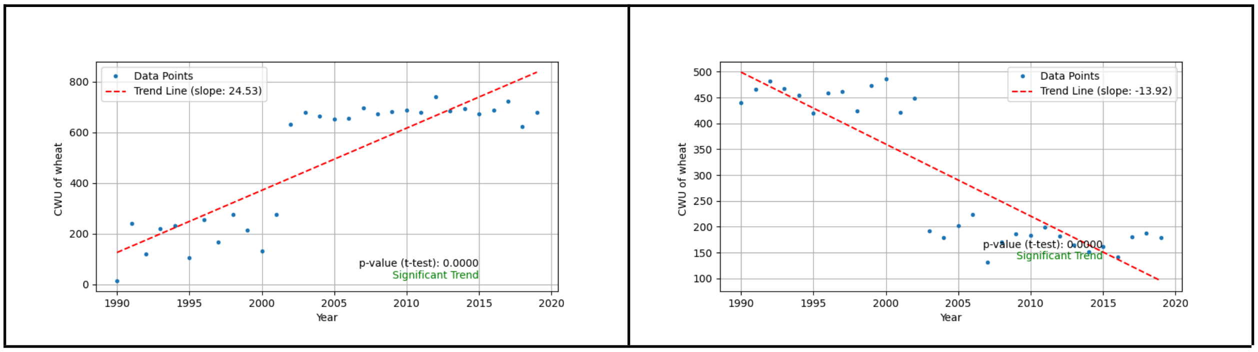


Figure 4-36- Trends with the highest and lowest slope for wheat in Italy

The highest slope of the trend line is 24.53, meaning that, on average, the CWU for wheat increased by 24.53 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed increasing trend is highly unlikely to be due to random chance, confirming a significant upward trend in the water use for wheat cultivation in southern Italy, region of Puglia, over these years.

The lowest slope of the trend line is -13.92, meaning that, on average, the CWU for wheat decreased by 13.92 millimeters per year over the observed period. The p-value associated with this trend is 0.0000, indicating that the trend is statistically significant. This very low p-value suggests that the observed decreasing trend is highly unlikely to be due to random chance, confirming a significant downward trend in the water use for wheat cultivation in northern Italy, region of Veneto, over these years.

Conclusion

This study aimed to quantify the total unit water footprint (m^3/ton year) and crop water use (CWU) (mm/year) of tomatoes, maize, and wheat in the Mediterranean region, particularly Italy, from 1990 to 2019. The study also assessed and compared the impact of climate variability on the water use of these crops and provided insights into sustainable water management practices that can mitigate the adverse effects of climate change on agriculture in the Mediterranean region.

5-1-Findings

The analysis revealed several key insights into the water use patterns of tomatoes, maize, and wheat.

5-1-1-Mediterranean Sea Basin

Tomatoes demonstrated the highest average CWU at 800 mm, followed by maize at 1600 mm, and wheat at 800 mm. The variability in water use, as indicated by the standard deviation, was highest for maize (800 mm), suggesting that maize water use is more affected by climate variability compared to tomatoes (500 mm) and wheat (350 mm). The coefficient of variation (CV) showed that wheat had the highest relative variability (0.75), followed by tomato (0.7) and maize (0.6), indicating that wheat water use fluctuates more.

In terms of trends, all crops showed significant trends in CWU according to P-values. The highest increase in CWU for tomatoes was observed in Syria (+44.07 mm/year), whereas the highest decrease was in southeastern Greece (-23.98 mm/year). For maize, the highest increase was in Lebanon (+56.37 mm/year), and the lowest was in northern Italy (-3.72 mm/year). Wheat had the highest increase in Cyprus (+29.23 mm/year) and the most significant decrease also in Cyprus (-26.94 mm/year).

5-1-2-Italy

In Italy, the average CWU for tomatoes was 580 mm, maize was 530 mm, and wheat was 485 mm. wheat again showed the highest variability in water use with a standard deviation of 250 mm, compared to tomatoes at 230 mm and maize at 200 mm. The coefficient of variation (CV) reflected this, with wheat at 0.5, tomato at 0.5, and maize at 0.44.

The trends in Italy were consistent with the Mediterranean Basin. The highest increase in CWU for tomatoes in Italy was in southeastern Italy, Puglia (+21.79 mm/year), and the highest decrease was in northern Italy, Emilia-Romagna (-5.45 mm/year). For maize, the highest increase was also in southeastern Italy, Puglia (+18.22 mm/year), with the lowest in northern Italy, Emilia-Romagna (-3.72 mm/year). Wheat had the highest increase in southeastern Italy, Puglia (+24.53 mm/year) and the most significant decrease in northern Italy, Veneto (-13.92 mm/year).

5-1-3-Crop water use in Mediterranean Sea Basin

The study analyzed the crop water use (CWU) of tomatoes, maize, and wheat across various countries in the Mediterranean region, focusing on average CWU, standard deviation (Std Dev), coefficient of variation (CV), p-value, and slope of the trend. The following table summarizes these metrics:

Table 5-1- Crop water use metrics by pixels in countries or region

Country/Region	Crop	Average CWU (mm)	Std Dev (mm)	CV	P-value	Slope (mm/year)
Syria	Tomato	710	451	0.61	0.000	44.07
Greece	Tomato	489	252	0.51	0.000	-23.98
Lebanon	Maize	1599	761	0.48	0.000	56.37
Italy	Maize	528	44	0.08	0.000	-3.72
Cyprus	Wheat	423	303	0.72	0.000	29.23
Cyprus	Wheat	723	283	0.39	0.000	-26.94
Puglia	Tomato	426	223	0.52	0.000	21.79
Emilia-Romagna	Tomato	576	61	0.1	0.000	-5.45
Puglia	Maize	406	180	0.44	0.000	18.22
Emilia-Romagna	Maize	528	44	0.08	0.000	-3.72
Puglia	Wheat	482	246	0.51	0.000	24.53
Veneto	Wheat	297	139	0.47	00.000	-13.92

From the table summarizing crop water use (CWU) metrics, it is evident that countries in the Mediterranean region display varying trends for tomatoes, maize, and wheat. These differences highlight the interactions between climate change and agricultural water use.

In Syria (near to southeastern Turkey), the average CWU for tomatoes stands at 710 mm, with a standard deviation of 451 mm, a coefficient of variation (CV) of 0.61, and a significant p-value of 0.000. The slope of +44.07 mm/year indicates a substantial increase in CWU, suggesting that climate change is leading to higher water requirements for tomato crops. This increase could potentially enhance yields if managed properly, but it also underscores the need for efficient irrigation practices to prevent overuse of water resources. In contrast, Southeastern Greece shows a decrease in CWU for tomatoes, with the average CWU of 489 mm, a standard deviation of 252 mm, a CV of 0.51, and a p-value of 0.000. The slope of -23.98 mm/year reflects reduced water availability, which could lead to water stress and lower yields unless efficient water use practices are implemented. This highlights the importance of adapting water management strategies to ensure sustainable tomato production under changing climatic conditions.

Southern Lebanon exhibits the highest increase in CWU for maize, with an average of 1599 mm, a standard deviation of 761 mm, a CV of 0.48, and a p-value of 0.000. The slope of +56.37 mm/year indicates significant climate-induced changes, potentially improving maize yields with adequate water management. This substantial increase in water use emphasizes the need for effective irrigation techniques to maximize the benefits of increased water availability without leading to resource depletion. Conversely, in northern Italy, maize shows a reduction in CWU with an average of 528 mm, a standard deviation of 44 mm, a CV of 0.08, and a p-value of 0.000. The negative slope of -3.72 mm/year suggests decreasing water availability, which could negatively affect yields if not addressed through improved water efficiency practices. This scenario underscores the necessity for drought-resistant crop varieties and water-saving technologies to sustain maize production.

Cyprus and the most significant decrease in CWU. The average CWU is 423 mm, with a standard deviation of 303 mm, a CV of 0.72, and a p-value of 0.000. The region shows a positive slope of +29.23 mm/year and a negative slope of -26.94 mm/year with the average CWU, standard deviation and CV equal to 723 mm, 283 mm and 0.39, respectively, which reflects substantial climate variability. This dual trend indicates the complexity of managing water use in the face of changing climatic conditions, requiring adaptive strategies to balance water availability and crop yield.

In Southeastern Italy, Puglia, increasing trends in CWU are observed for all three crops. Tomatoes show a slope of +21.79 mm/year, maize +18.22 mm/year, and wheat +24.53 mm/year. These increasing trends suggest improving water availability and potential yield benefits with proper irrigation management. The focus in this region should be on optimizing irrigation techniques to harness the benefits of increased water without causing over-irrigation issues. Northern Italy, on the other hand, shows decreasing trends in CWU for tomatoes, maize, and wheat. Tomatoes have a slope of -5.45 mm/year, maize -3.72 mm/year, and wheat -13.92 mm/year. These trends indicate potential water stress across all crops, highlighting the need for enhanced water-saving practices and the development of drought-resistant crop varieties. Implementing efficient water management strategies is crucial to maintaining crop yields in the face of reduced water availability.

5-1-3-1-Country with the most Climate Change Impact

Based on the analysis, Cyprus exhibits the most significant climate change impact in terms of yield and crop water use, particularly for wheat. The region shows both the highest positive slope (+29.23 mm/year) and the most significant negative slope (-26.94 mm/year), reflecting substantial climate-induced variability. This significant fluctuation underscores the critical need for effective water management and adaptive strategies to mitigate the adverse effects of climate change and sustain agricultural productivity. Developing resilient agricultural practices and investing in efficient irrigation technologies are essential steps to ensure the long-term sustainability of crop production in this region.

5-1-4-Impact of crop water use (CWU) on crop yield

The relationship between crop water use (CWU) and crop yield is intricate and influenced by a multitude of factors, including climate, soil conditions, irrigation practices, and overall crop management strategies. This section delves into the specific impacts of CWU changes on the yields of tomatoes, maize, and wheat across the Mediterranean Sea Basin and Italy, highlighting the potential positive and negative outcomes of varying water use trends.

Tomato

In the Mediterranean Sea Basin, the highest increase in CWU for tomatoes was observed in Syria, with an annual rise of 44.07 mm. This increase in water availability can significantly enhance tomato growth, potentially leading to higher yields if other factors such as soil fertility and temperature are optimal. However, excessive water use may result in waterlogging or nutrient leaching, which could adversely affect yield quality and quantity. Conversely, in southeastern Greece, a decrease in CWU by 23.98 mm per year may improve water use efficiency and lead to better yields if water stress is effectively managed. On the downside, reduced water availability can cause water stress, leading to lower yields.

In Italy, southeastern regions saw the highest increase in CWU for tomatoes at 21.79 mm per year. Increased irrigation in these areas may enhance yields if managed properly. However, over-irrigation poses risks, including root diseases and reduced crop quality. In northern Italy, a decrease in CWU by 5.45 mm per year suggests that water-saving practices might improve efficiency and yield if stress is avoided, but potential water stress could decrease yield.

Maize

For maize in the Mediterranean Sea Basin, the highest CWU increase was recorded in southern Lebanon, with an annual rise of 56.37 mm. This increased water supply can boost yields if other conditions are favorable. However, over-irrigation can lead to soil degradation and reduced yields. In northern Italy, a decrease in CWU by 3.72 mm per year highlights the potential for efficient water use to maintain or improve yields. Yet, reduced water availability may limit yields if water stress occurs.

In Italy, southeastern regions experienced a high CWU increase for maize at 18.22 mm per year. Adequate irrigation here can improve maize yields, though risks of over-irrigation include nutrient loss and soil erosion. In northern Italy, a decrease in CWU by 3.72 mm per year indicates that improved water use efficiency may sustain or enhance yields, but insufficient water could reduce yield.

Wheat

In the Mediterranean Sea Basin, the highest increase in CWU for wheat was observed in Cyprus, with an annual rise of 29.23 mm. Increased water availability in these areas can enhance yields if other factors are suitable. However, excess water may cause lodging or disease, reducing yield. Conversely, a significant decrease in CWU by 26.94 mm per year in the same region indicates that efficient water management can maintain yield levels, although water stress can significantly reduce yields.

In Italy, the highest CWU increase for wheat was in southeastern regions, at 24.53 mm per year. Proper irrigation can lead to higher yields, though excessive water might reduce grain quality and yield. In northern Italy, a decrease in CWU by 13.92 mm per year highlights the potential for water efficiency measures to maintain or improve yields, but insufficient water can cause significant yield reduction.

The impact of increased CWU on crop yields can be beneficial if managed properly, as it can enhance growth and yield. However, over-irrigation can lead to problems such as waterlogging, nutrient leaching, and increased disease prevalence. On the other hand, decreased CWU can maintain or even improve yields through improved water use efficiency. Nevertheless, reduced water availability can cause water stress, reducing crop yields.

5-2- Implications

The findings highlight the relationship between climate variability and crop water use. The significant trends observed in CWU for tomatoes, maize, and wheat suggest that climate change and variability have a pronounced impact on agricultural water use in the Mediterranean region. Tomatoes generally have the highest water use and show the most significant upward trend, particularly in regions like Syria and southeastern Italy (Puglia), indicating that these areas are experiencing increased water availability or more intensive irrigation practices. Maize, while showing a high average CWU and significant variability, also exhibits increasing trends, especially in southern Lebanon and southeastern Italy (Puglia). Wheat, on the other hand, presents a mixed picture with decreasing trends in several areas, particularly Cyprus and northern Italy, indicating potential water stress and the need for more efficient water management practices.

5-3-Mediterranean Region agriculture adaptation

Adapting Mediterranean agriculture to the challenges posed by climate change requires a multifaceted approach that enhances resilience, efficiency, and sustainability. Water management is a critical component in this effort. Efficient irrigation systems, such as drip irrigation, subsurface irrigation, and well-managed sprinkler systems, can deliver water directly to plant roots, minimizing evaporation losses and reducing water wastage. Additionally, water harvesting and storage solutions, including rainwater harvesting and the construction of reservoirs and ponds, are vital for capturing excess water during wet periods for use during droughts. Soil moisture management techniques, such as mulching and conservation tillage, can also play a crucial role by reducing evaporation and preserving soil moisture and structure. Advanced irrigation scheduling, supported by soil moisture sensors and weather forecasting, allows for the optimization of irrigation timing and amounts, ensuring water is used only when necessary.

Crop management strategies must also be adapted to cope with changing climate conditions. Selecting and breeding crop varieties that are drought-resistant and heat-tolerant will help ensure that agricultural production can withstand increased temperatures and reduced water availability. Crop rotation and diversification, including the practice of intercropping, can improve soil health, reduce pest and disease cycles, and enhance biodiversity and resilience. Adjusting planting dates to align with shifting climate patterns will help avoid peak stress periods, further optimizing crop yields.

Effective soil and land management practices are essential for maintaining soil health and fertility in the face of climate change. Soil conservation practices such as terracing can reduce soil erosion on slopes and improve water infiltration. Planting cover crops during off-seasons protects soil from erosion and enhances fertility. Enhancing organic matter in the soil through composting and green manure can improve its water-holding capacity and nutrient levels, contributing to more resilient agricultural systems.

Technological innovations offer significant potential for adapting Mediterranean agriculture to climate change. Precision agriculture, utilizing GPS and drones, enables farmers to monitor crop health, soil conditions, and water use, allowing for data-driven management decisions. Automated equipment can reduce labor and increase efficiency in planting, irrigation, and harvesting. Climate-smart agriculture (CSA) integrates climate adaptation and mitigation practices into agricultural management, improving resilience and reducing greenhouse gas emissions.

Policy and economic measures are necessary to support the adoption of sustainable practices. Providing financial incentives or subsidies for farmers who adopt efficient agricultural technologies and practices can encourage widespread adoption. Implementing water pricing strategies and regulations can promote efficient water use and prevent over-extraction of water resources. Developing and promoting insurance schemes to protect farmers from climate-related losses and encouraging income diversification can help reduce dependency on a single crop or agricultural activity, enhancing economic resilience.

Community and knowledge sharing are also crucial for successful adaptation. Capacity building and training programs can educate farmers on sustainable practices, new technologies, and climate adaptation strategies. Investing in research and development to create new crop varieties, irrigation technologies, and farming practices tailored to the Mediterranean climate will provide the necessary tools for adaptation. Collaborating with research institutions, agricultural organizations, and farmers can facilitate knowledge sharing and innovation.

Nature-based solutions offer additional benefits for adapting Mediterranean agriculture. Integrating trees and shrubs into agricultural landscapes through agroforestry can improve biodiversity, soil health, and water retention. Restoring and protecting wetlands can enhance natural water filtration, flood control, and biodiversity, providing vital ecosystem services.

Furthermore, To mitigate the adverse effects of water stress, efficient irrigation strategies such as drip irrigation and precise irrigation scheduling are essential. Additionally, developing drought-tolerant tomato varieties and employing mulching techniques to conserve soil moisture can further enhance resilience against water scarcity.
To sustain maize production in the Mediterranean region, adopting efficient irrigation practices is critical. Subsurface irrigation, which reduces water loss through evaporation, can significantly improve water use efficiency. Additionally, selecting drought-resistant corn varieties and optimizing planting dates to avoid peak stress periods are crucial strategies. These practices, combined with advanced irrigation scheduling and precision agriculture technologies, can help farmers manage water resources more effectively and maintain corn yields under changing climatic conditions.

5-4-Future developments

Considering the ongoing challenges posed by climate change, future research and developments should focus on:
1. Advanced Climate Modeling: Enhance predictive models to better understand and anticipate the impacts of climate variability on crop water use in the Mediterranean region. Accurate models can help farmers and policymakers make informed decisions about water management.
2. Innovative Water Management Practices: Develop and implement new water-saving technologies and practices to improve irrigation efficiency and crop resilience. Innovations such as precision irrigation and drought-tolerant crop varieties can help mitigate the impacts of climate change.

3. Genetic Research: Invest in the development of crop varieties with improved water-use efficiency and drought tolerance. Genetic advancements can lead to crops that require less water while maintaining or improving yields.
4. Policy and Regulation: Strengthen policies and regulations to promote sustainable water use in agriculture and provide incentives for adopting efficient water management practices. Policies that support water conservation and efficient irrigation can help ensure the long-term sustainability of water resources.
5. Community Engagement: Foster community-based water management initiatives to ensure equitable and efficient use of water resources. Engaging local communities in water management can lead to more effective and sustainable practices.

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