Transition
Innovative resilient farming systems
in Mediterranean environments

Deliverable 4.2

Maps and calculations of projected climate scenario impact on the extension of baseline systems and innovative systems

Document history

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PRIMA
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IN THE MEDITERRANEAN AREA

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ABRV	Definition of the abbreviation
AOI	Area Of Interest
CDD	Maximum number of consecutive dry days
CFD	Maximum number of consecutive frost days
CSU	Maximum number of consecutive summer days
CWD	Maximum number of wet days
FD	Frost days
ID	Ice days
GSL	Growing season length
Pr	Precipitation
R10mm	Heavy precipitation days
R20mm	Very heavy precipitation days
RR	Precipitation sum
SU	Summer days
Tas	Average temperature
Tasmax	Maximum temperature
Tasmin	Minimum temperature
TNn	Minimum of daily minimum temperature
TX	Mean of daily maximum temperature
TXx	Maximum of daily maximum temperature

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1. INTRODUCTION

1.1. Innovative agricultural systems to mitigate the adverse effects of climate change in the Mediterranean

Climate change poses a significant challenge to agriculture, altering weather patterns, increasing the frequency of extreme weather events, and affecting the overall productivity of agricultural systems. These changes disrupt traditional farming practices, challenge food security, and threaten the livelihoods of millions of farmers worldwide. As temperatures rise and precipitation patterns shift, crops may suffer from heat stress, drought, or flooding, leading to reduced yields and increased vulnerability. Therefore, understanding and mitigating the impacts of climate change on agriculture is crucial for ensuring sustainable food production and resilience in agricultural systems. At the same time, unsustainable agricultural practices have a disproportionate contribution to climate change and environmental degradation globally, and the Mediterranean region in particular (European Environment Agency 2019). Therefore, a transition to more sustainable agricultural practices is both timely and urgent (FAO and The Nature Conservancy 2021).

The Mediterranean region is particularly vulnerable to the impacts of climate change (Cos et al. 2022), due to its unique climatic conditions characterized by hot, dry summers and mild, wet winters (Zittis et al. 2022). This region, which spans Southern Europe, North Africa, and the Middle East, relies heavily on agriculture as a critical component of its economy and culture (Duarte et al. 2021). However, climate change threatens to exacerbate existing water scarcity issues, reduce soil fertility, and increase the prevalence of pests and diseases. In the Mediterranean, traditional crops such as olives (Fraga et al. 2020, grapes (Tscholl et al. 2024) or cereals (Pérez-Méndez et al. 2021) are at risk, necessitating the development of adaptive strategies to safeguard agricultural productivity and sustainability.

Innovative agricultural systems, including cover cropping, the introduction of new crops, and the adoption of sustainable agricultural practices, offer promising solutions to the challenges posed by climate change (FAO and The Nature Conservancy 2021). Cover cropping involves planting specific crops to protect and enrich the soil during off-seasons, enhancing soil health, reducing erosion, and often contributing to enhanced nutrient and carbon topsoil concentration. Introducing new crops that are more resilient to changing climatic conditions can diversify agricultural production and reduce risk. Sustainable agricultural practices, such as conservation tillage, agroforestry, and organic farming, aim to increase resource-use efficiency, enhance biodiversity, and reduce or mitigate greenhouse gas emissions. These innovations are critical in building resilient agroecosystems capable of withstanding climate variability and contributing less to climate and environmental degradation.

In the Mediterranean context, adopting these innovative agricultural systems can significantly mitigate the adverse effects of climate change. Cover cropping can improve soil moisture retention and fertility, essential for crop growth in this water-scarce region (Herencia 2018; Moukanni et al. 2022). New crops, tailored to withstand higher temperatures and reduced water availability, can ensure continued agricultural productivity. Sustainable practices, like efficient water management and integrated pest management (Caselli and Petacchi 2021), can conserve vital resources and reduce the environmental footprint of farming. By focusing on these strategies, Mediterranean agriculture can become more adaptable and resilient, ensuring food security and supporting rural livelihoods.

To effectively adapt to and mitigate climate change impacts, it is essential to project future climate scenarios and map their potential effects on agriculture. Utilizing high-resolution satellite data and advanced climate models, researchers can develop detailed maps that illustrate the risks and vulnerabilities of different crops under various climate scenarios. These maps can inform policymakers, farmers, and stakeholders about the most vulnerable areas and crops, guiding the implementation of adaptive measures. By integrating climate projections with spatially explicit agroclimatic indices, allows for the development of targeted strategies to enhance the resilience of Mediterranean agroecosystems, ultimately contributing to sustainable agricultural development in the face of climate change.

1.2. Context of the deliverable

The aim of this deliverable is to map climate conditions across various agro-climatic regions and using knowledge from experts gathered during project execution to estimate the effect of climate change of plant productivity and growth in five selected regions. Cross-referencing this data with spatially explicit agroclimatic indices and current crop extensions from high-resolution satellite data, existing databases and maps, assesses each crop’s requirements against simulated climate scenarios. This approach projects the risks faced by each crop under different climate conditions, producing relevant maps to inform adaptive strategies for sustainable agriculture.

2. METHODOLOGY

Data Sources

The data for this project were gathered from various sources, focusing on projected agroclimatic indicators and future climate parameters for the Mediterranean region. These datasets provide comprehensive information on future climate conditions, and crop maps.

2.1. Areas of Interest

The study focused on specific areas within the Mediterranean region (Southern France, Sicily, southern Italy; Catalonia, Northeastern Spain; Sétif Northern, Algeria, Behia and Kafr Elsheihk Governates Northern Egypt). Shapefiles outlining these Areas Of Interest (AOI) and individual farm boundaries were loaded and reprojected to match the coordinate reference system of the climate projection data. These AOIs were used to crop and mask the reference datasets, ensuring that subsequent analyses were focused on relevant regions.

2.2. Climatic Data

Agroclimatic indicators (Table 1) were downloaded from COPERNICUS (Nobakht et al. 2019). The HadGEM2-ES Model (UK Met Office, UK) for the RCP2.6 scenario was chosen. These datasets were cropped to the AOIs, and specific agroclimatic indicators were extracted. Data for the periods 2011-2024 and 2057-2070 were selected to represent past/current and future scenarios, respectively. For a full description of the agroclimatic parameters and how they were derived see Item 1 in Annex.

Table 1. Full list of agroclimatic indicators. For each case study country this list was modified according to agronomic information provided by case study partners

Indicator abbreviation	Indicator	Unit
R10mm	Heavy precipitation days	Day
R20mm	Very heavy precipitation days	Day
RR	Precipitation sum	mm

Indicator abbreviation	Indicator	Unit
SU	Summer days	Day
TX	Mean of daily maximum temperature	K
TXx	Maximum of daily maximum temperature	K
CDD	Maximum number of consecutive dry days	Day
CFD	Maximum number of consecutive frost days	Day
CSU	Maximum number of consecutive summer days	Day
CWD	Maximum number of wet days	Day
GSL	Growing season length	Day
TNn	Minimum of daily minimum temperature	K

Future, high-resolution EURO-CORDEX data. In addition to the agroclimatic indicators, high-resolution (12.5 km) climate projection data from regional GCMs (EURO-CORDEX) (Copernicus Climate Change Service 2019) was used. EURO-CORDEX are the highest resolution climate projection data available at a European scale with a daily temporal resolution. The HadGEM2-ES Model (UK Met Office, UK) for the RCP2.6 scenario was chosen. We made a conscious decision to use the RCP 2.6 scenario to address a policy-relevant research question rather than to make a claim about likely futures. RCP 2.6 represents the stringent mitigation pathway and is has been widely used as a benchmark for assessing the potential benefits of strong mitigation efforts. While recent assessments indicate that current global emissions trajectories are closer to higher-emission scenarios, we believe that RCP 2.6 remains scientifically valuable for understanding the avoided impacts, system sensitivities, and adaptation or mitigation requirements to achieve low-emissions futures. Our results should thus be interpreted as conditional outcomes under ambitious mitigation, not as a prediction of the most likely scenario.

EURO-CORDEX data was downloaded [average temperature at 2m (tas), maximum temperature (tasmax), minimum temperature (tasmin), and precipitation (pr)] and cropped each variable to the AOIs of the case studies.

2.3. Current crop and agricultural practices

High-resolution satellite data were used to map current crop extensions within the AOIs. Because for each case study country there are different available data regarding crop type cover and agricultural practices maps, for each case study country different sources were used. Cover crop data were also loaded, cropped, and masked to fit the AOIs.

These maps were visualized to provide a baseline understanding of current agricultural landscapes.

For all north Mediterranean case studies, a high-resolution, remote sensing-derived cover crop percentage index covering all of Europe (Fendrich et al. 2023) was used. A percentage of cover crop at 100m resolution for AOIs in France, Spain and Italy was mapped.

Adding to the cover crop mapping, for the French case study we also extracted data from the farmers Geospatial Aid applications (GSAA) from France (EUROCROPS database, Schneider et al. 2023). GSAA are declarations made by farmers that geolocate their parcels and asign them to specific crop types. We extracted crop types that are related to the AOI in France (orchards: Orchard, Berry, Bigarreau cherry, Plum; vegetables: Tomato, Zucchini / Pumpkin, Carrot, Tomato for processing, Aubergine, Spinach, Lamb's lettuce, Leek, Rocket, Pumpkin / Red kuri squash, Lettuce / Batavia / Oak leaf) and mapped them to French AOI. For Spain, we mapped olive groves, vineyards and annual crops and for Italy olive groves using the latest Corine Land Cover dataset.

For the south Mediterranean case studies, in lieu of crop type maps, very high-resolution cropland layers from ESA WORLDCOVER was used. For a list of all the crop-type, cropland and agricultural practice maps used in this report see the Table 2.

Table 2. Crop-type, cropland and agricultural practice maps used in this report

Dataset	Type of map	Country
Cover crop percentage per 100m raster cell	Agricultural practice map	France, Italy, Spain
GSAA/LPIS farmer declarations	Crop-type map	France
Corine Land Cover	Crop-type map	France, Italy, Spain
ESA WOLDCOVER	Cropland mapping	Egypt, Algeria

2.4. Farm level statistical and climate projection analysis

For the case study countries with a significant amount of case study farms (France, Spain), we conducted farm-level analysis of agroclimatic indicators. Algeria (3 farms), Italy (4), and Egypt (1) were excluded from farm-level analysis due to the lack of power for statistical analysis, but were included in all agroclimatic indicators and climate dynamics analyses. Agroclimatic indicators were extracted from the climatic datasets for each farm within the AOIs. The data were then merged to form a comprehensive dataset covering all indicators and time periods. Mixed-effects models were employed to statistically test the differences between agroclimatic indicators across two time periods (2011-2024 and 2057-2070). The lmer function from the lme4 package (Bates et al. 2024) was used to fit these models, with farm ID as a random effect to account for variability between farms. All agroclimatic parameters of Table 1 were analyzed for the spring and summer months, and the results summarized to identify significant changes over time.

2.5. Mapping Climate Projections

For each agroclimatic indicator, lower quartile, upper quartile, mean, and variability (standard deviation) were calculated for the spring and summer seasons in both time periods (2011-2024 and 2057-2070). These statistics can provide insights into the variability and expected changes in climatic conditions affecting agriculture. Maps were created to visualize the calculated quartiles, means, and variability for each agroclimatic indicator. Consistent color scales were used across all maps to facilitate comparison. The maps highlighted regions within the AOIs where significant changes in climate conditions are expected, aiding in the identification of vulnerable areas. The resulting maps were exported as TIFF files, with each file corresponding to a specific agroclimatic indicator for both periods. These visualizations serve as valuable tools for stakeholders, providing clear and actionable insights into the projected impacts of climate change on Mediterranean agriculture.

Using high-resolution EURO-CORDEX data, a spatio-temporal analysis of climate dynamics was conducted through exploring and measuring different dimensions of climate change in space and time. Specifically, we mapped the estimated change trends (2006-2060) via slope estimation, probability of local climate extremes for precipitation, average temperature, maximum temperature and minimum temperature. For precipitation, maximum and minimum temperature, we also mapped the probability for novel climate creation and standardized local anomalies taking 1950-2001 as a reference period. All analyses were conducted using the climetrics library in R (Taheri et al. 2024). In what follows below, for all climate dynamics analyses, we refrain from discussing trends only visible at outer boundaries of the AOIs, to avoid biases potentially introduced both by ocean/land mixels (mixed ocean/land cells coastal grid cells) and by clipping along a shoreline (checkerboard pattern of mixels).

2.6. Effects of climate change on crops

For each AOI, the impact of new climate regimes on crop productivity and health was estimated by overlaying the crop and agricultural practices maps with the maps of climate change projections. These projections included agroclimatic indicators, climatic extremes, novel climates, climate parameter trends and local anomalies. Using local agronomic knowledge and through the literature review, narrative results were provided on how a changing climate will affect agriculture in all AOIs. Additionally, policy recommendations were provided on how to adapt agriculture to this specific changing climate.

3. RESULTS

3.1. France

Mixed-effects models for the 18 farms in the French AOI suggest significant changes are underway for the majority of agroclimatic indicators. Heavy precipitation events (R10mm and R20mm) and total precipitation will increase in the spring months. At the same time, maximum temperatures will increase in the spring and summer months, while summer days and total spring-summer consecutive summer days and dry days will also increase (SU, CSU, CDU). Finally, frosty days in the spring-summer season seem to be slightly decreasing.

Table 3. Mixed-effects model results for agroclimatic indicators at the farm level in France. Significance levels henceforth in the document (< 0.05; ** < 0.01; *** < 0.001)*

Parameter	Season	Estimate	Std. error	t value
R10mm (days per 10-days)	spring	0.07*	0.031	2.402
	summer	0.01	0.023	0.588
R20mm (days per 10-days)	spring	0.08***	0.017	5.056
	summer	-0.02	0.012	-1.807
RR (mm)	spring	2.06**	0.782	2.639
	summer	-1.27*	0.590	-2.164
SU (days per 10-days)	spring	0.50***	0.112	4.531
	summer	-0.03	0.030	-1.030
TX (K)	spring	0.60***	0.112	5.419
	summer	1.23***	0.091	13.575
TXx (K)	spring	0.66***	0.104	6.407
	summer	1.28***	0.083	15.442
CDD (days per season)	spring-summer	2.08***	0.390	5.340

Parameter	Season	Estimate	Std. error	t value
CFD (days per season)	spring-summer	-0.08*	0.042	-2.108
CSU (days per season)	spring-summer	8.02***	1.052	7.632

Our results indicate changes in 9 agroclimatic indicators over two time periods of analysis in the French AOI: 2011-2024, and 2057-2070 (Supplementary Material – French AOI). Small and larger differences are visible. The differences reflect the changes revealed by the farm-level analysis, with a spatial perspective. Particularly interesting are the marked increases in maximum temperature and maximum temperature variability (FIG 1), total precipitation and heavy precipitation events, considering that these maps refer to days per 10-day intervals. Significant increases in consecutive dry days and consecutive summer days are also observed.

The analysis of climate dynamics reveals that there are important spatial-temporal trends for many variables across the French AOI (Supplementary Material – Climate Dynamics). Analysis of all climate variables under consideration (average temperature, maximum temperature, minimum temperature, precipitation) indicates that new climatic conditions will prevail. The maps below (Fig. 2) indicate the probability of local climate extremes for average temperature, maximum temperature, minimum temperature, and precipitation. This analysis estimates the probability that values outside the (0.05, 0.95) values of current climate will occur per year. It can be seen that there is a high probability of values outside the current climate for precipitation. As noted in the Methods section, care should be taken to avoid interpreting single and coastal pixel as indicating dynamics due to possible land/ocean mixed pixel bias.

High standardized local anomaly scores correspond to large changes in temperature and precipitation, which only appear in the coastal, non-agricultural part of the French AOI. Novel climates quantify the probability of novel climates, i.e., climate conditions that are outside the current. The main agricultural area of the French AOI is expected to experience new climatic conditions under RCP2.6. Finally, for the French AOI we can see that all climatic variables are increasing, albeit unevenly across space. Maximum temperature and precipitation seem to be increasing across the AOI with high intensity.

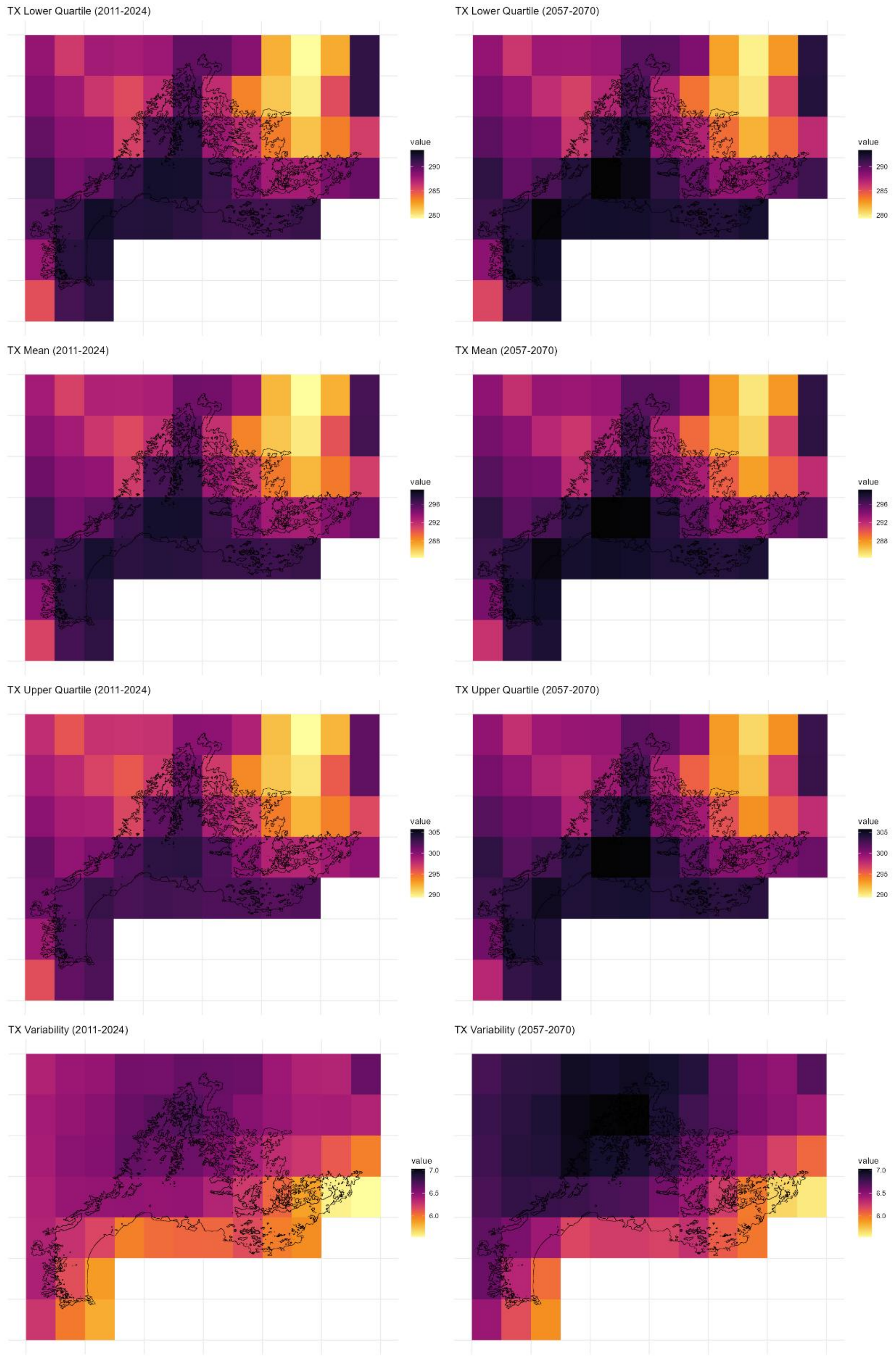

Figure 1. Frost days (FD, days every 10-days) change over the French AOI. Top left: mean values 2011-2024; Top right: mean values (2057-2070); Middle left: upper (90%) quartile 2011-2024; Middle left: lower (10%) quartile 2011-2024; Bottom left: variability (standard deviation) 2011-2024; bottom right: variability (standard deviation 2057-2070).

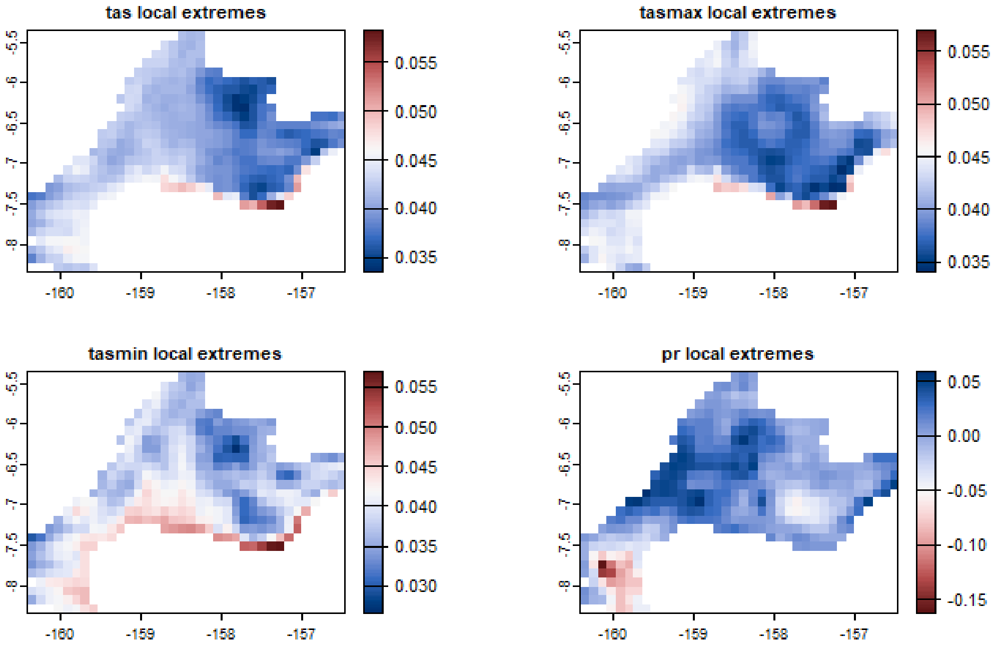

Figure 2. Probability of local climate extremes for average temperature (tas), maximum temperature (tasmax), minimum temperature (tasmin), and precipitation (pr) in the French AOI.

Overlaying the crop-type and cover crop with the agroclimatic indicator and climate dynamic maps, in combination with the mixed-effect models at the farm scale offers interesting insights for the French AOI. Orchards in central and northeastern regions face reduced frost and icing days, which can benefit tree health but may disrupt chilling requirements for some fruit varieties. Increased heavy rain and very heavy rain days can cause waterlogging, root diseases, soil erosion, and increased disease pressure, while changes in total precipitation can lead to water stress or waterlogging, impacting growth and fruit quality. More summer days and increased maximum temperatures can cause heat stress, sunburn on fruits, and higher water demands, while extreme heat events can result in fruit drop and increased mortality of young trees. Vegetables in these regions may experience extended growing seasons due to reduced frost and icing days, but increased heavy and very heavy rain days can lead to flooding, soil erosion, and disease outbreaks. Extended dry spells and prolonged summer periods can cause severe water stress, heat stress, reduced crop quality, and increased water requirements, while extreme heat can lead to crop failure and reduced yields.

Orchards in central and northeastern regions are highly susceptible to heat stress, altered blooming times, reduced fruit quality, and increased disease susceptibility due to standardized local anomalies, novel climates, and trends in average and maximum temperatures. Minimum temperature trends and local extremes can reduce frost damage but disrupt dormancy and chilling requirements, while precipitation trends and extremes pose risks of water stress, waterlogging, and increased disease incidence. Vegetables in these regions face challenges such as heat stress, reduced growth rates, lower yields, and increased water requirements due to extreme temperature trends and anomalies. Additionally, changes in precipitation patterns threaten vegetable growth and yield, necessitating new water management practices and potentially increasing irrigation costs.

Table 4. Main results of the spatial analysis of agroclimatic indicators.

Crop Type	***Agroclimatic Indicator***	***Regions Affected***	***Potential Impacts***
Orchards	ID	Central and Northeastern	Reduced icing events, potentially beneficial for tree health and fruit set.
Orchards	RR10mm	Central and Northeastern	Increased heavy rain days can lead to waterlogging, root diseases, and physical damage to trees.
Orchards	R20mm	Central and Northeastern	Higher frequency of very heavy rain can cause soil erosion, waterlogging, and increased disease pressure.
Orchards	RR	Central and Northeastern	Changes in total precipitation can lead to water stress or waterlogging, affecting growth and fruit quality.
Orchards	SU	Central and Northeastern	More summer days can lead to heat stress, increased irrigation needs, and potential sunburn on fruits.
Orchards	TX	Central and Northeastern	Increased maximum temperatures can cause heat stress, reduced fruit quality, and increased water demand.
Orchards	TXx	Central and Northeastern	Extreme heat events can lead to fruit drop, sunburn, and increased mortality of young trees.
Orchards	CDD	Central and Northeastern	Increased dry spells can lead to severe water stress, reduced fruit quality, and increased irrigation needs.
Orchards	CFD	Central and Northeastern	Extended frost periods can cause significant damage to buds and blossoms, reducing yield and fruit quality.
Orchards	CSU	Central and Northeastern	Prolonged summer periods can result in heat stress, sunburn on fruits, and higher water requirements.
Vegetables	FD	Central and Northeastern	Reduced frost days can extend the growing season but may also affect crops that require vernalization.
Vegetables	ID	Central and Northeastern	Fewer icing days can reduce cold damage and extend the growing season.
Vegetables	RR10mm	Central and Northeastern	Increased heavy rain days can cause flooding, soil erosion, and disease outbreaks.
Vegetables	R20mm	Central and Northeastern	Very heavy rain days can damage crops, cause soil erosion, and increase disease incidence.
Vegetables	RR	Central and Northeastern	Changes in total precipitation can lead to water stress or waterlogging, impacting growth and yield.
Vegetables	SU	Central and Northeastern	More summer days can result in heat stress, higher irrigation needs, and reduced crop quality.

Crop Type	*Agroclimatic Indicator*	*Regions Affected*	*Potential Impacts*
Vegetables	TX	Central and Northeastern	Higher maximum temperatures can cause heat stress, reduced photosynthesis, and increased water requirements.
Vegetables	TXx	Central and Northeastern	Extreme heat can lead to crop failure, reduced yields, and increased irrigation needs.
Vegetables	CDD	Central and Northeastern	Extended dry spells can lead to water stress, reduced growth rates, and lower yields.
Vegetables	CFD	Central and Northeastern	Prolonged frost periods can damage crops, delay planting, and reduce overall productivity.
Vegetables	CSU	Central and Northeastern	Prolonged summer periods can cause heat stress, reduced photosynthesis, and increased water demand.
Cover crop	FD	Central and Northeastern	Reduced frost damage, potentially insufficient chilling hours for some cover crops, affecting growth cycles.
Cover crop	ID	Central and Northeastern	Reduced icing events, lower physical damage to plants but may still affect early growth stages.
Cover crop	RR10mm	Central and Northeastern	Increased heavy rain days can lead to waterlogging, soil erosion, and increased disease pressure.
Cover crop	R20mm	Central and Northeastern	Higher frequency of very heavy rain can cause significant soil erosion, waterlogging, and nutrient leaching.
Cover crop	RR	Central and Northeastern	Changes in total precipitation can lead to water stress or waterlogging, impacting growth and soil health.
Cover crop	SU	Central and Northeastern	More summer days can cause heat stress, increased irrigation needs, and potential reduction in biomass production.
Cover crop	TX	Central and Northeastern	Increased maximum temperatures can cause heat stress, reduced growth rates, and higher water requirements.
Cover crop	TXx	Central and Northeastern	Extreme heat events can lead to plant wilting, reduced biomass, and increased irrigation needs.
Cover crop	CDD	Central and Northeastern	Increased dry spells can lead to severe water stress, reduced growth, and increased irrigation needs.
Cover crop	CFD	Central and Northeastern	Extended frost periods can cause significant damage to cover crops, affecting soil protection and health.
Cover crop	CSU	Central and Northeastern	Prolonged summer periods can result in heat stress, reduced growth rates, and increased water demand.

3.2. **Spain**

Table 4 indicates that spring experiences increased rainfall and higher temperatures, while summer shows decreased rainfall but higher temperatures. Notably, extreme weather days increase in the spring-summer period, with a significant rise in hot days and a reduction in frost days. Summer rainfall declines significantly, while both maximum and minimum temperatures rise sharply in both seasons. Overall, there is a trend towards warmer and more variable climatic conditions. Drought and summer days do not seem to change significantly, only the latter in the spring will be increased.

Table 5. Mixed-effects model results for agroclimatic indicators at the farm level in Spain.

Parameter	Season	Estimate	Std_Error	t_value
R10mm (days per 10-days)	spring	0.06**	0.01	3.47
	summer	-0.06***	0.01	-3.72
R20mm (days per 10-days)	spring	0.02**	0.00	3.0
	summer	-0.07***	0.0	-7.42
RR (mm)	spring	2.25***	0.47	4.73
	summer	-2.51***	0.46	-5.36
SU (days per 10-days)	spring	0.60***	0.08	7.19
	summer	-0.00	0.01	-0.33
TXx (K)	spring	0.59***	0.05	10.17
	summer	0.91***	0.05	16.94
TNn (K)	spring	0.63***	0.07	8.84
	summer	0.89***	0.05	17.52
CDD (days per season)	spring-summer	-0.064	0.23	-0.26
CFD (days per season)	spring-summer	-0.149***	0.01	-10.68
CSU (days per season)	spring-summer	8.124***	0.71	11.35
CWD (days per season)	spring-summer	0.636***	0.04	15.09

Agroclimatic indicator maps for Spain reveal distinct spatial and temporal patterns (Supplementary Material – French AOI). CDD (Fig. 3) show a marked increase in the southern regions, with mean and maximum values significantly higher in the future period. Conversely, CFD and FD are more prevalent in the northern regions, though these will decrease over time, indicating a warming trend. CSU and SU are more frequent in the south, with both the mean and upper quartile values indicating prolonged summer conditions. CWD, in contrast, are more common in the north, though there will be a slight reduction in their occurrence over time. Rainfall-related indicators, such as R10mm and R20mm, show higher mean values in the north, with variability suggesting more significant fluctuations in heavy rainfall events in the future. Lastly, TNn maps indicate a significant increase in both mean and upper quartile values, particularly in the northern regions, suggesting warmer conditions in the future. The variability of TNn also shows notable fluctuations, indicating that while the overall trend is warming, there are still significant year-to-year variations. Temporal trends indicate a general warming pattern.

Analysis of all climate variables under consideration (average temperature, maximum temperature, minimum temperature, precipitation) in the Spanish AOI indicates that new climatic conditions will prevail (Supplementary Material – Spain, Climate dynamics). In the maps below (Fig. 4) it can be seen that for all variables there is a high probability of values outside the current climate with high frequency. For average and minimum temperature this probability is higher in the southern and eastern regions of the AOI. For maximum temperature in the eastern regions, while in relation to precipitation new extremes will mostly appear in south-western region of the AOI.

Standardized local anomalies analysis indicates that the southern and eastern regions will be see climate envelopes outside the current condition with a higher probability. Furthermore, in terms of novel climatic conditions (as represented by temperature and precipitation variables), the south-western regions seem to be the most affected in the future.

Finally, for the Spanish AOI it can be observed that all climatic variables are increasing, albeit unevenly across space. Precipitation seems to be increasing across the AOI with high intensity, exception for the very southern part. Temperature trends are more geographically uneven, with the southern and northern part more affected by temperature increases.

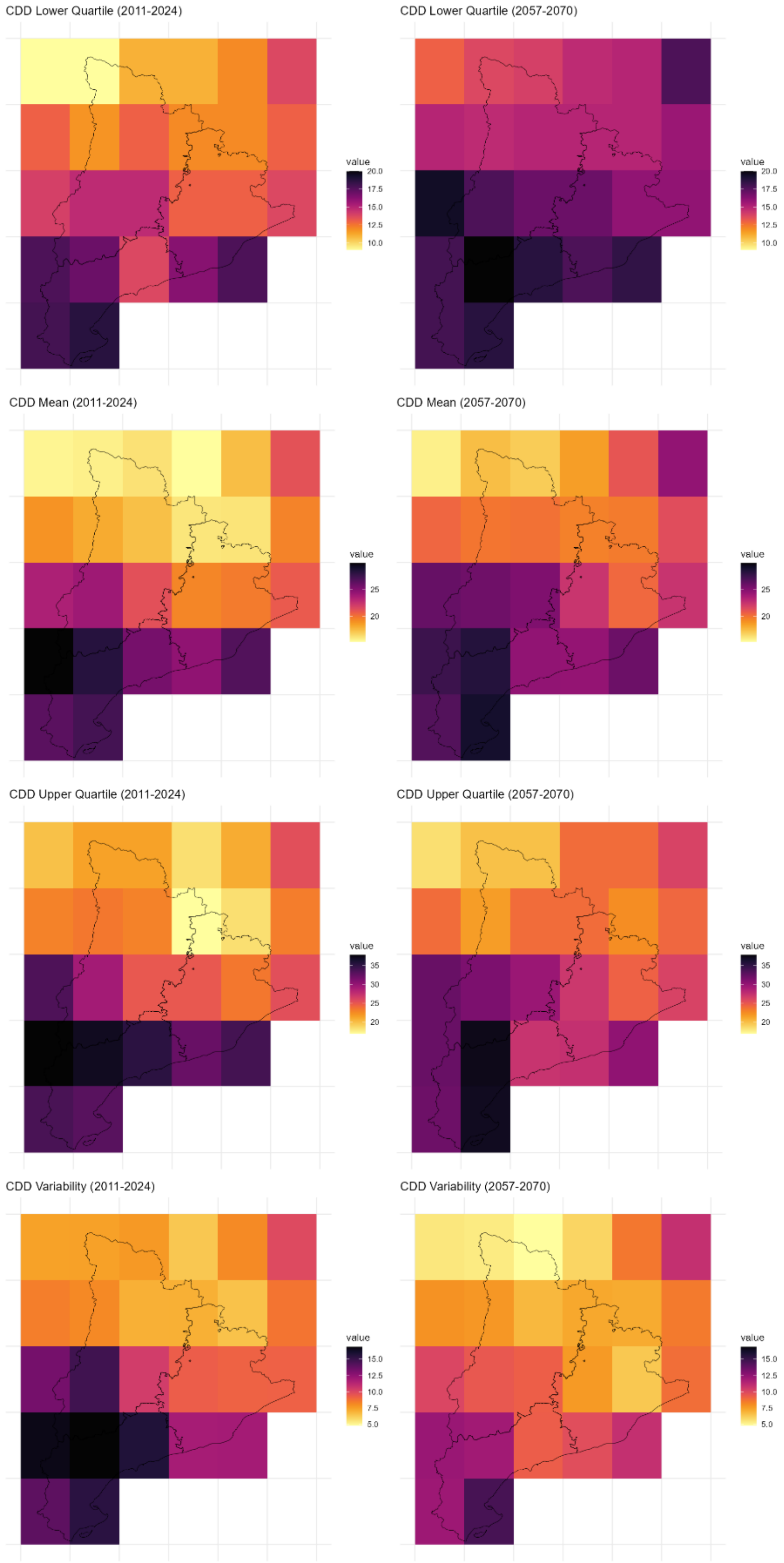

Figure 3. Consecutive Dry Days (days) change over the Spanish AOI, in Catalonia. Top left: lower (10%) quartile (2011-2024); Top right: lower (10%) quartile (2057-2070). Top middle left: mean values 2011-2024; Top middle right: mean values (2057-2070); Low middle left: upper (90%) quartile 2011-2024; Low middle left: upper (90%) quartile 2011-2024; Bottom left: variability (standard deviation) 2011-2024; bottom right: variability (standard deviation 2057-2070).

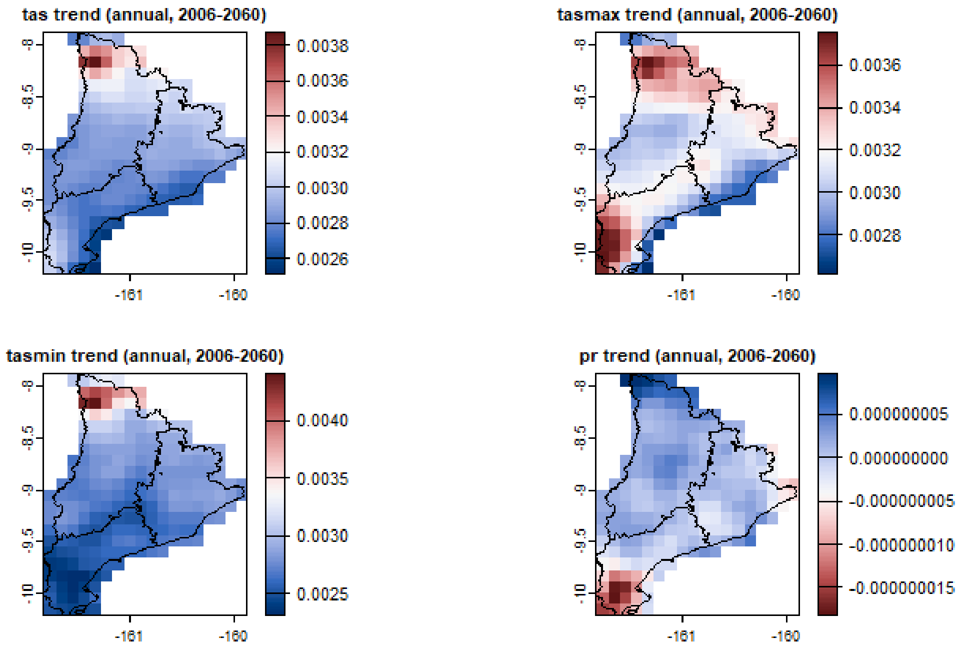

Figure 4. Climate trends (time ~ climate variable regression slopes) for temperature (tas), maximum temperature (tasmax), minimum temperature (tasmin), and precipitation (pr) in the Spanish AOI.

Overlaying the crop-type and cover crop with the agroclimatic indicator and climate dynamic maps in Spain, allows us to infer important insights olive, vine and cereal cultivation under different climates.

The spatial and temporal dynamics of agroclimatic indicators show varied impacts on crops depending on the region. Northern and western regions benefit from reduced frost and increased rainfall but face waterlogging risks. Southern and eastern regions see favorable conditions for ripening and growth but must manage increased heat and drought stress. Central regions benefit from consistent moisture but need to manage disease risks due to increased wet days. Adaptation strategies tailored to these specific conditions are essential to sustain crop productivity and quality.

The analysis shows that central regions face increased heat stress and waterlogging risks for olives and vineyards due to local climate extremes, along with significant climate shifts requiring adaptation for all crops. Eastern regions experience climate shifts that necessitate adaptive management for olives and vineyards. Northern regions, particularly for annual crops, face challenges due to novel climates, necessitating the introduction of resilient crop varieties. Northeastern regions show trends of increased temperatures benefiting ripening but raising heat stress and water demand for olives and vineyards, while central regions must address exacerbated drought conditions impacting annual crops. Central regions face increased heat stress and waterlogging risks for cover crops due to local climate extremes, requiring careful water management. Eastern regions experience significant climate anomalies, necessitating adaptive management strategies to maintain cover crop productivity. Northern regions face challenges due to novel climates, which may require the introduction of climate-resilient cover crop varieties. Northeastern regions show increasing temperature trends, which can enhance growth but also increase heat stress and water demand, while central regions must address exacerbated drought conditions impacting cover crops' water availability and growth.

Table 6. Table summarizing the results of the spatio-temporal analysis of agroclimatic indicators.

Crop Type	***Indicator***	***Area***	***Impact***
Vineyards, Olives	FD and ID	North	Reduced frost damage, beneficial for growth
Annual Crops	R10mm and R20mm	North	Adequate moisture but risk of waterlogging and disease
Vineyards, Olives	TXx, CDD, SU, CSU	South	Favorable ripening, increased heat stress, need for water management
Annual Crops	TXx, CDD, SU, CSU	South	Increased drought stress, potential yield reduction
Vineyards, Olives	TNn, (RR)	East	Reduced frost risk, variable moisture impacting crop stability
Annual Crops	TNn, Rainfall Variability (RR)	East	Supportive growth conditions, inconsistent water supply
Vineyards, Olives	R10mm and R20mm, FD	West	Adequate moisture, reduced frost risk, potential waterlogging
Annual Crops	R10mm and R20mm, FD	West	Reduced frost risk, manage waterlogging risk
Vineyards, Olives	CWD, RR	Central	Consistent moisture, potential disease risk
Annual Crops	CWD, RR	Central	Adequate moisture, risk of waterlogging and disease
cover crops	TXx, CDD, SU, CSU	South	Favorable growth, increased heat stress, need for water management
cover crops	TNn, (RR)	East	Reduced frost risk, variable moisture impacting crop stability
cover crops	R10mm and R20mm, FD	West	Adequate moisture, reduced frost risk, potential waterlogging
cover crops	CWD, RR	Central	Consistent moisture, potential disease risk

3.3. **Italy**

The analysis of RR20mm and TNn over Sicily reveals notable changes between current (2011-2024) and future (2057-2070) conditions (Supplementary Material – Sicily AOI). Mean RR20mm is projected to slightly increase in the southern and central regions, and increase more in the northern region of Sicily, indicating more very heavy rainfall events in the future, which is accompanied by increased variability in these areas. This suggests a higher risk of extreme weather patterns, with some areas experiencing drought and others potential flooding. For TNn, the future projections show a substantial increase in minimum temperatures across all regions, with the central and northern parts experiencing the most pronounced changes. This warming trend suggests milder winters, which could reduce frost damage but also disrupt chilling requirements for certain crops. The increase in temperature variability indicates that while overall temperatures will rise, there could still be significant fluctuations, posing challenges for agricultural planning and crop resilience.

Local climate extremes over the region highlight significant patterns (Fig. 5) (excluding mixed cells from the analysis). For temperature averages, local minimum extremes are more pronounced in the western and central parts, indicating these areas are likely to experience higher temperature spikes. The minimum temperature extremes show a similar pattern, with higher values in the central regions, suggesting warmer nights. Precipitation extremes are notably higher in the eastern and western part, indicating a higher probability of extreme rainfall events, which can lead to increased risks of flooding and associated soil erosion. These patterns suggest that the western and central regions will face more frequent and intense heat events, while the eastern region will need to manage the impacts of more frequent and intense rainfall.

The annual trends for 2006-2060 (Fig. 6) indicate a significant increase in both average temperatures (tas) and maximum temperatures (tasmax) across the region, with the most pronounced warming in the central, northern and eastern areas. Minimum temperatures (tasmin) also show a strong upward trend, particularly in the central and southeastern regions. Precipitation trends (pr) indicate slight increases across the region, with the eastern areas showing more pronounced increases.

The western, central and south-eastern regions exhibit higher standardized anomalies, suggesting significant deviations from the norm, while eastern regions show a higher, but still concetrated presence of novel climates, indicating areas that will experience unprecedented climate conditions. These changes highlight the need for targeted adaptation strategies to manage emerging climate risks in these regions.

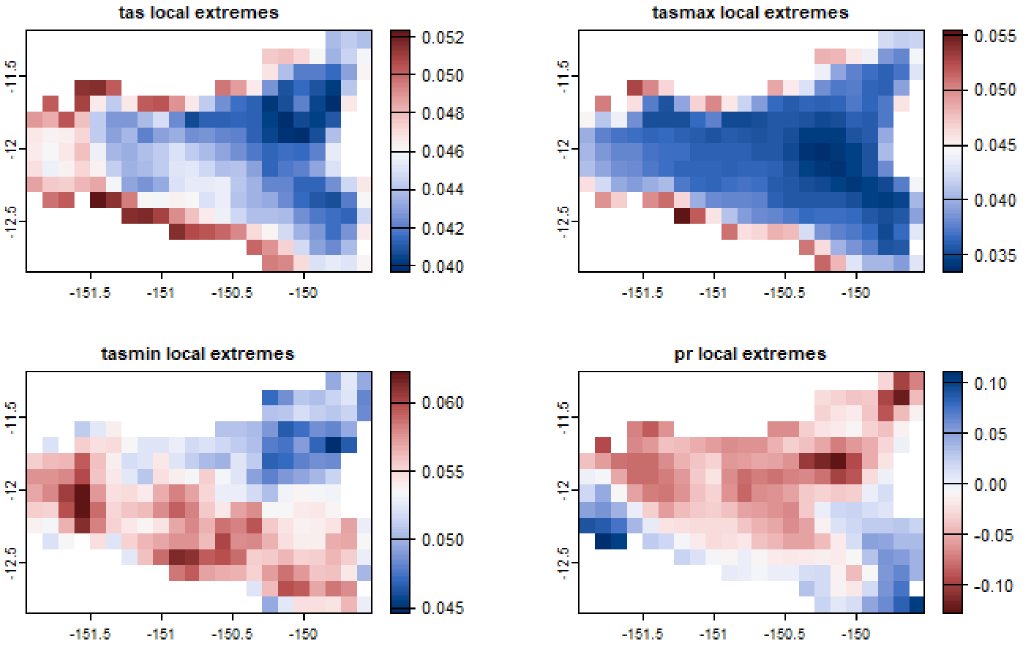

Figure 5. Probability of local climate extremes for average temperature (tas), maximum temperature (tasmax), minimum temperature (tasmin), and precipitation (pr) in Sicily, the Italian AOI.

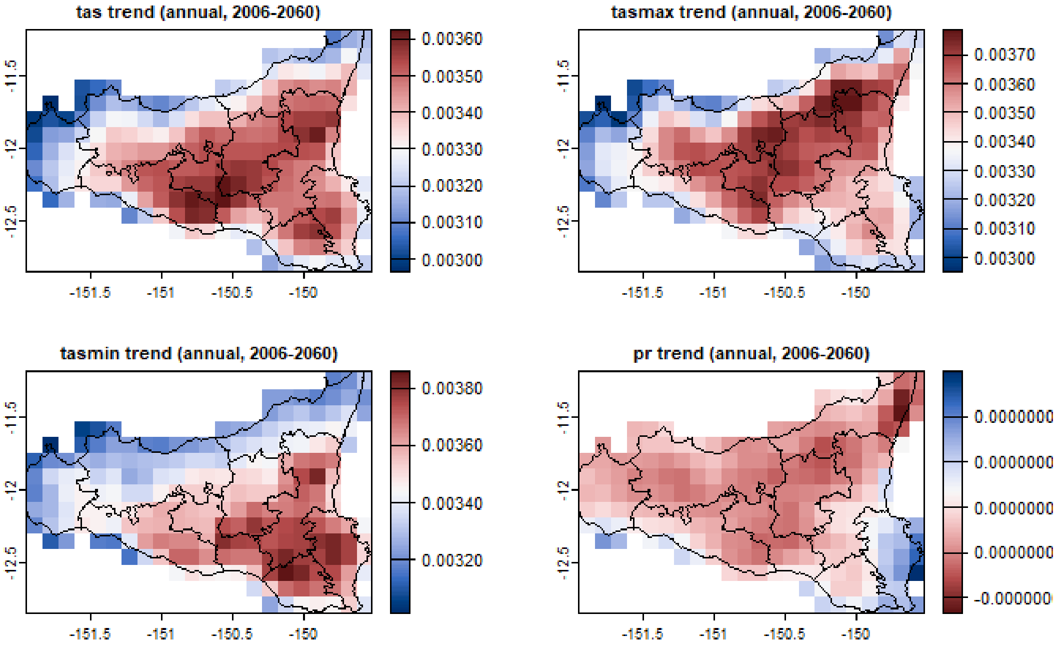

Figure 6. Climate trends (time ~ climate variable regression slopes) for temperature (tas), maximum temperature (tasmax), minimum temperature (tasmin), and precipitation (pr) in Sicily, the Italian AOI.

Overlaying the crop-type and cover crop with the agroclimatic indicator and climate dynamic maps in Sicily, allows us to infer important insights olive cultivation and cover cropping under different climates.

The spatial and temporal dynamics of agroclimatic indicators RR20mm and TNn suggest varying impacts on olive groves and cover crops. For olive groves, reduced frost risk and potential waterlogging issues are prominent, while cover crops benefit from reduced frost damage but face challenges from increased temperature variability. Adaptive strategies such as efficient irrigation, soil conservation practices, and selecting temperature-resilient crop varieties are crucial to mitigate these impacts and sustain agricultural productivity in the affected regions.

The spatial and temporal dynamics of climate indicators such as temperature and precipitation extremes, standardized anomalies, novel climates, and long-term trends indicate significant impacts on both olive groves and cover crops (Table 10). These impacts necessitate the implementation of adaptive management strategies tailored to the specific conditions of each region to sustain agricultural productivity and soil health in the face of climate change.

Table 7. Summary table of climate dynamics impacts in the Italian AOI.

Crop Type	*Climate Indicator*	*Region*	*Future Effect*
Olive Groves	tas Extremes	Western, Central	Higher evapotranspiration, increased water demand
Olive Groves	tasmax Extremes	Western, Central	More frequent heatwaves, need for heat management
Olive Groves	tasmin Extremes	Central	Warmer nights, potential disruption of flowering cycles
Olive Groves	pr Extremes	Eastern	Increased drought stress due to reduced precipitation
Olive Groves	Standardized Local Anomalies	Western, Central	Increased climate variability, adaptive management needed
Olive Groves	Novel Climates	Northern, Eastern	Challenges to traditional practices, need for new strategies
Olive Groves	tas Trend	Central, Western	Higher evapotranspiration rates, increased water demand
Olive Groves	tasmax Trend	Central, Western	Increased need for heat management strategies
Olive Groves	tasmin Trend	Central	Potential disruption of flowering cycles
Olive Groves	pr Trend	Eastern	Increased drought stress
Cover Crops	tas Extremes	Western, Central	Higher evapotranspiration, increased water demand
Cover Crops	tasmax Extremes	Western, Central	More frequent heatwaves, need for more frequent irrigation
Cover Crops	tasmin Extremes	Central	Warmer nights, enhanced survival rates
Cover Crops	pr Extremes	Eastern	Increased drought stress due to reduced precipitation
Cover Crops	Standardized Local Anomalies	Western, Central	Stress on crops, affecting soil health

Cover Crops	Novel Climates	Northern, Eastern	Selection of new cover crop varieties necessary
Cover Crops	tas Trend	Central, Western	Increased water requirements
Cover Crops	tasmax Trend	Central, Western	Impact on growth and effectiveness of cover crops
Cover Crops	tasmin Trend	Central	Potential disruption of growth cycles
Cover Crops	pr Trend	Eastern	Increased drought stress

3.4. **Egypt**

The agroclimatic indicators for spring and summer in Egypt show notable changes between current and future conditions (Supplementary Material – Egypt AOI). For RR10mm, the mean values and variability are expected to decrease in the future, indicating a reduction in the frequency of heavy rainfall events. This trend is observed across the entire region. In terms of SU (Fig 7), the future projections show a significant increase in the number of summer days, particularly in the central and northern regions. This increase in summer days indicates a shift towards hotter conditions. TXx and TX both show an upward trend in mean values and variability. This suggests that extreme heat events will become more frequent and intense. For TNn, future projections indicate an increase in mean values and variability, especially in the northern and central regions.

The climate change indicator maps for the region reveal several key trends and potential impacts (Supplementary Material – Egypt Climate Dynamics). The first set of maps shows the probability of local extremes, with a noticeable increase in all temperature and precipitation extremes. This suggests that the region will experience more frequent extreme weather events, including higher temperatures and potentially less precipitation.

For Egypt an additional metric was calculated, the annual probability of local dryness extremes (Fig. 8). Local dryness extremes in Northern Egypt show significant spatial variability. Areas with higher probability of dryness extremes are primarily concentrated in the north, western and south-western parts of the region. In general, the probability of local dryness extremes decreases from the periphery towards the central regions of the map.

The standardized local anomalies map indicates significant deviations from historical climate norms, especially in the northern parts of the region, suggesting that these areas will undergo substantial climate shifts (Supplementary Material – Egypt Climate Dynamics). The novel climates map shows regions where new climate conditions are expected to emerge, particularly in the northern and eastern-central areas, indicating that these regions will face unprecedented climatic conditions that may challenge existing agricultural practices. The trends map indicates an overall increase in temperature and precipitation trends from 2006 to 2060. The southestern and central parts of the region show the highest increases in average and maximum, temperature, the northern parts an increase in minimum temperature, while precipitation trends also indicate an increase, particularly in the northern regions.

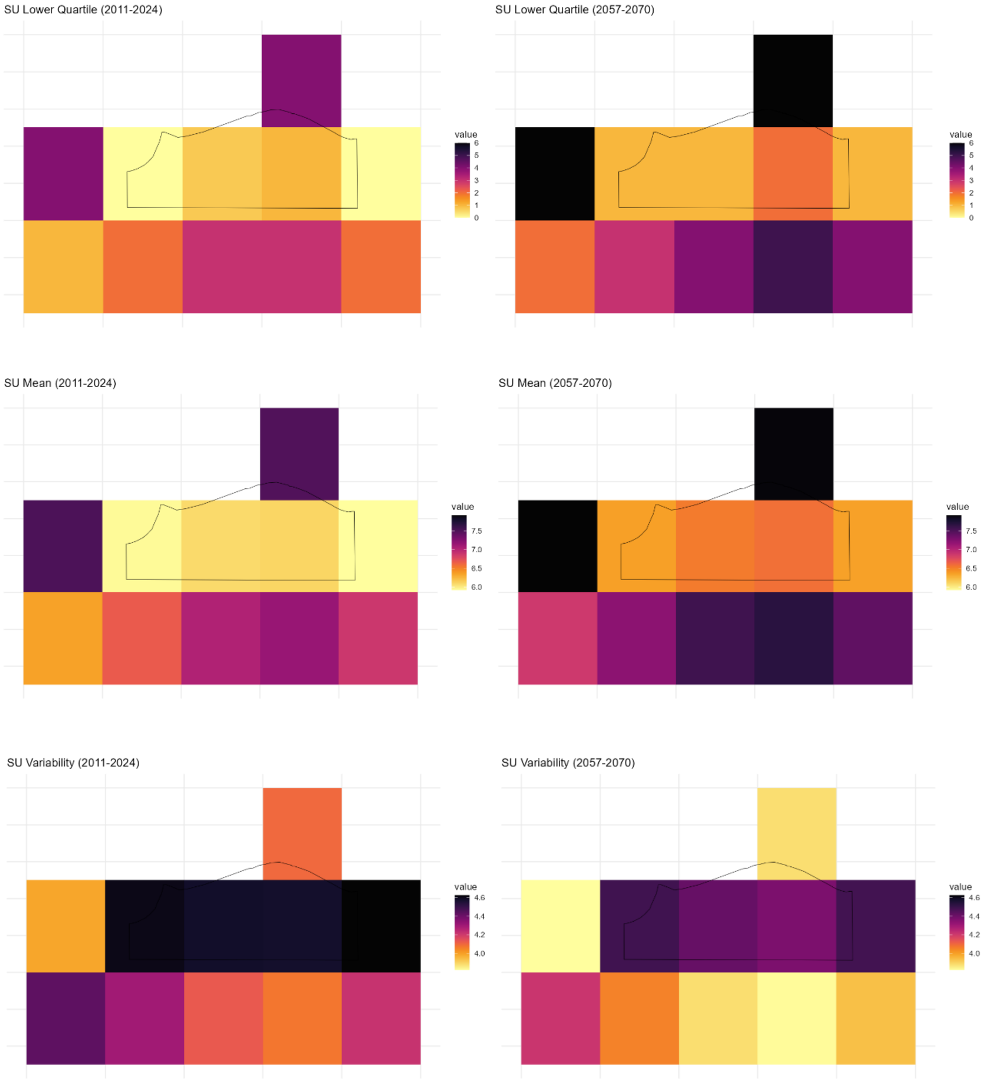

Figure 7. Summer days (SU, days every 10-days) change at the Egyptian AOI. Top left: mean values 2011-2024; Top right: mean values (2057-2070); Middle left: upper (90%) quartile 2011-2024; Middle left: Upper (10%) quartile 2011-2024; Bottom left: variability (standard deviation) 2011-2024; bottom right: variability (standard deviation 2057-2070).

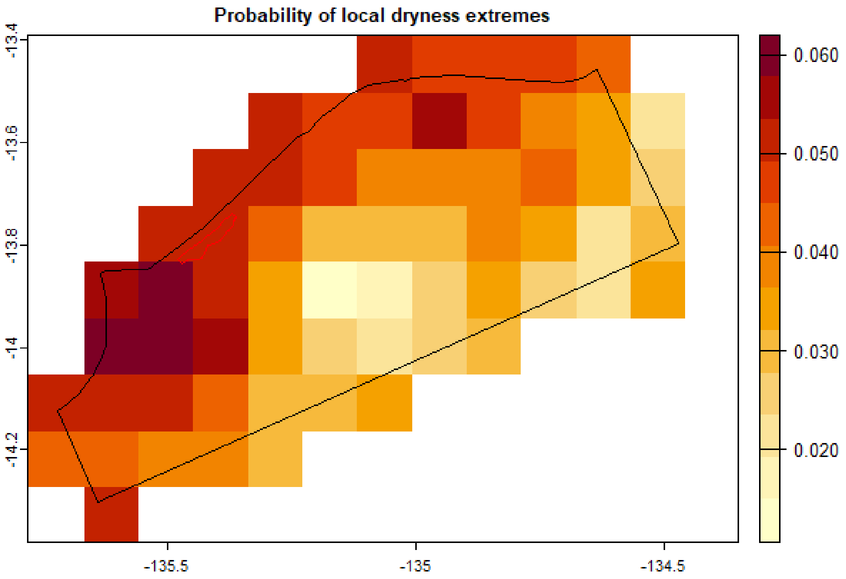

Figure 8. Increase in annual probability of local dryness extremes compared to now, where values for temperature are at the top 95% of the historical record, and precipitation values at the 5% low. The black polygon represents the wider AOI in Egypt, while the smaller red polygon represent the Mutubas study area.

For Egypt, there is no relatively recent available map of crop type in the AOI. We acquired a Sentinel-2-derived 10m resolution map of croplands (ESA WORLDCOVER, 2021) to overlay on the agroclimatic indicator and climate dynamics maps.

A slight reduction in CWD in the western region will lead to higher water demand for tomatoes, while the increase in CDD in central and northern regions necessitates increased irrigation for tomatoes and stresses rice. Additionally, the increase in CSU, TNn, TX, RR, and SU across the AOI will generally result in higher water demand, increased heat stress on crops like tomatoes, and mixed impacts on rice and soil conditions (Table 8).

The table details the impacts of various climate change indicators on cropland, emphasizing regional overlaps. In the Northern regions, increased temperature extremes (tas, tasmax) and trends (tasmin) may lead to significant heat stress and reduced crop productivity, while higher precipitation trends could both benefit water availability and risk waterlogging. In the Western regions, rising temperature trends (tas) and minimum temperature extremes (tasmin) may lessen frost risk but increase heat stress, and novel climates may challenge current agricultural practices. Central and Eastern regions face increased drought stress due to higher probabilities of local dryness extremes and lower precipitation extremes, necessitating adaptive measures to sustain crop yields.

Table 8. Summary table of climate dynamics of crop health in the Egyptian AOI.

Climate Change Indicator	***Overlap Area***	***Impact on Cropland***
tas local extremes	High overlap in Northern regions	Increased temperature extremes may lead to heat stress on crops, affecting yield and quality.
tasmax local extremes	High overlap in Northern regions	Higher maximum temperature extremes may cause heat stress and reduce crop productivity.
tasmin local extremes	High overlap in Western regions	Increased minimum temperature extremes may reduce frost risk but increase heat stress on crops.
pr local extremes	High overlap in Eastern regions	Lower precipitation extremes may lead to water stress
Probability of local dryness extremes	High overlap in Central and Northern regions	Higher probability of local dryness extremes may increase drought stress on crops.
tas trend	High overlap Western region	Rising annual temperature trends may increase heat stress and water demand.
tasmax trend	High overlap in the Southern Region	Increasing maximum temperature trends may lead to higher heat stress and irrigation needs.
tasmin trend	High overlap in Northern region	Increasing minimum temperature trends may reduce frost risk but increase heat stress.
pr trend	High overlap in the Northern region	Rising annual precipitation trends may lead to higher water availability but also waterlogging risk.
Standardized Local Anomalies	High overlap in Northern regions	Significant climate anomalies may require adaptive agricultural practices.
Novel climates	High overlap in Northern and Western regions	Novel climates may challenge existing agricultural practices, requiring new crop varieties.

3.5. **Algeria**

For Algeria, we did not perform an analysis of agroclimatic indicators. The AOI for Algeria is comparatively small, and only cell of the agroclimatic indicator maps fall within it. We only focused on climate dynamics, which use the higher resolution EURO-CORDEX dataset.

Overall, the maps indicate that northern and western regions will face significant challenges due to increased temperature extremes and variability, while western regions will need to adapt to rising minimum temperatures and novel climate conditions (Figs. 9 and 10). Southern regions will need to address the increased likelihood of dryness extremes, variability in precipitation and increased average and maximum temperatures. Local anomalies seem to be predicted at the western areas of AOI, indicated out-of-the-ordinary temperature extremes.

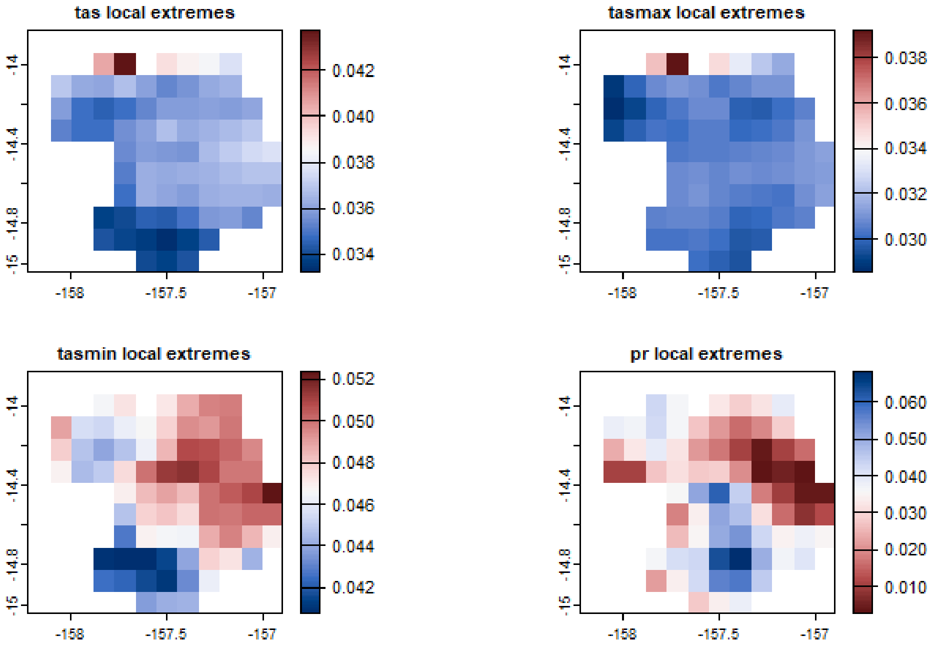

Figure 9. Probability of local extremes for average temperature (tas), maximum temperature (tasmax), minimum temperature (tasmin), and precipitation (pr) at the Algerian AOI.

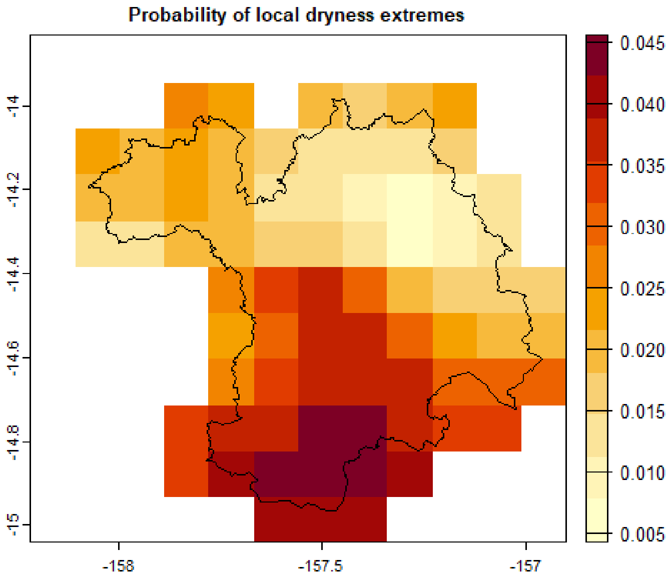

Figure 10. Increase in annual probability of local dryness extremes compared to now, where values for temperature are at the top 95% of the historical record, and precipitation values at the 5% low. The black polygon represents the wider AOI in Algeria.

The analysis of climate change impacts on cropland in Northern Algeria reveals several critical trends. Increased temperature extremes, particularly in the very northern regions, are expected to cause significant heat stress, reducing crop yield and quality. Higher maximum temperature extremes will further exacerbate heat stress and decrease productivity. In the eastern regions, increased minimum temperature extremes will also contribute to heat stress. Southern regions face lower precipitation extremes, leading to water stress. Central and southern regions show a higher probability of local dryness extremes, increasing drought stress on crops. Annual temperature trends indicate rising temperatures, particularly in the southern region, necessitating increased water demand and heat stress management. Maximum temperature trends in the southern and central regions will heighten irrigation needs. While rising minimum temperature trends in the southern region may reduce frost risk, they will increase heat stress. In the northern region, rising annual precipitation trends may improve water availability. Significant climate anomalies in the northern and western regions will require adaptive agricultural practices. Novel climates emerging in the very northern and very southern regions will challenge existing agricultural practices, necessitating the introduction of new crop varieties.

Table 9. Summary of the effects of climate dynamics on croplands in Algeria.

Climate Change Indicator	***Overlap Area***	***Impact on Cropland***
tas local extremes	Very northern regions	Increased temperature extremes may lead to heat stress on crops, affecting yield and quality.
tasmax local extremes	Very northern regions	Higher maximum temperature extremes may cause heat stress and reduce crop productivity.
tasmin local extremes	Eastern regions	Increased minimum temperature extremes may increase heat stress on crops.
pr local extremes	Southern regions	Lower precipitation extremes may lead to water stress
Probability of local dryness extremes	Central and Southern regions	Higher probability of local dryness extremes may increase drought stress on crops.
tas trend (annual, 2006-2060)	Southern region	Rising annual temperature trends may increase heat stress and water demand.
tasmax trend (annual, 2006-2060)	Southern and Central Region	Increasing maximum temperature trends may lead to higher heat stress and irrigation needs.
tasmin trend (annual, 2006-2060)	Southern region	Increasing minimum temperature trends may reduce frost risk but increase heat stress.
pr trend (annual, 2006-2060)	Northern region	Rising annual precipitation trends may lead to higher water availability.
Standardized Local Anomalies	Northern / Western regions	Significant climate anomalies may require adaptive agricultural practices.
Novel climates	Very Northern and very southern regions	Novel climates may challenge existing agricultural practices, requiring new crop varieties.

4. CONCLUSIONS

The analysis of climate change impacts on Mediterranean agroecosystems reveals significant challenges and varied effects across different regions and crop types. Increased temperature extremes, changing precipitation patterns, and novel climates will necessitate adaptive measures to sustain crop productivity and quality (Tscholl et al. 2024). These changes will affect both tree and crop cultivation, leading to increased heat stress, water demand, and potential damage from extreme weather events (van Leeuwen et al. 2024). Effective management strategies will be crucial to mitigate these impacts and maintain agricultural sustainability (European Environment Agency 2019).

For southwestern France, the northern and central regions of the studied region will experience reduced frost days but increased heavy rainfall, which can benefit crops but also pose risks of waterlogging and disease. In Catalonia, Spain, northern regions will benefit from reduced frost and increased rainfall, while southern regions will face heat and drought stress. In Sicily, Italy, olive groves will experience reduced frost risk but face challenges from increased temperature variability, requiring adaptive irrigation and soil conservation practices. In Behia and Kafr Elsheihk Governates, Egypt, the reduction in cold wet days and increased summer days will lead to higher water demand and heat stress for tomatoes and mixed impacts on rice. In Sétif Algeria, increased temperature extremes and changing precipitation patterns will necessitate adaptive agricultural practices to manage heat and drought stress.

To address these challenges, each country will need to adopt specific adaptive strategies. In France, improving drainage systems and adopting disease management practices will be essential. Spain will need to focus on water management and selecting heat-tolerant crop varieties. Italy should implement efficient irrigation, soil conservation practices, and select temperature-resilient crop varieties. Egypt will benefit from enhanced irrigation infrastructure, soil moisture conservation practices, and selecting drought-resistant crop varieties. Algeria should focus on adaptive agricultural practices, such as introducing new crop varieties and improving water management.

A comprehensive strategy for Mediterranean agriculture should include region-specific adaptation measures, such as improved irrigation infrastructure, soil conservation practices, and the selection of heat and drought-tolerant crop varieties. Policymakers should support farmers through subsidies and incentives for adopting sustainable practices and investing in technology to improve water use efficiency. A roadmap for Mediterranean agriculture should prioritize resilience building, sustainable water management, and the development of climate-smart agricultural practices to ensure food security and agricultural sustainability in the face of climate change.

Table 10. Summary table for Deliverable 4.2, containing the main climate variables expected to change, the risks associated with them and suggestion for adaptation strategies.

Country	Variable(s) expected to change in future climate	Associated risk for plants	Possible adaptation strategies
Algeria	Increased temperature extremes; changing precipitation patterns (incl. dryness/drought stress)	Heat stress; water stress/drought stress	Introduce new crop varieties; improve water management (broader adaptive agricultural practices)
Egypt	Reduction in cold/wet days; increase in summer days (heat)	Higher water demand and heat stress (notably for tomatoes); mixed impacts by crop	Enhance irrigation infrastructure' soil moisture conservation practices; drought-resistant crop varieties
France	Reduced frost days; increased heavy rainfall	Lower frost damage but higher risk of waterlogging and disease pressure	Improve drainage systems; adopt disease management practices
Italy	Reduced frost risk; increased temperature variability	Lower frost damage; but greater stress/instability from temperature variability	Efficient irrigation; soil conservation practices; temperature-resilient crop varieties
Spain	North: reduced frost, increased rainfall; South: heat and drought stress	Heat stress and water stress (south); water-related disease/waterlogging risks where rainfall increases (north)	Water management; heat-tolerant crop varieties

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6. ANNEXES

ANNEX 1. Agroclimatic parameters for all case study countries and crops

Agroclimatic parameters for all case study countries and crops including full details on how each parameter is derived.

Parameter abbreviation	Parameter name	Parameter meaning	Unit
R10mm	Heavy precipitation days	Number of days per 10 days when RR > 10mm, where RR is the daily precipitation sum. This indicator provides information on crop damage and runoff losses.	Day
R20mm	Very heavy precipitation days	Number of days per 10 days when RR > 20mm, where RR is the daily precipitation sum. This indicator provides information on crop damage and runoff losses.	Day
RR	Precipitation sum	Sum of RR over 10 days, where RR is the daily precipitation sum. This indicator provides information on possible water shortage or excess.	mm
SU	Summer days	Number of days per 10 days when TX > 25°C, where TX is the daily maximum temperature. This indicator provides an indication of the occurrence of heat stress.	day
TX	Mean of daily maximum temperature	Mean value of TX over 10 days, where TX is the daily maximum temperature. This indicator provides information on long-term climate variability and change.	K

Parameter abbreviation	Parameter name	Parameter meaning	Unit
TXx	Maximum of daily maximum temperature	Maximum value of TX over 10 days, where TX is the daily maximum temperature. This indicator provides information on long-term climate variability and change.	K
CDD	Maximum number of consecutive dry days	Longest period of consecutive days when RR < 1mm, where RR is the daily precipitation sum. This indicator is used for drought monitoring.	Day
CFD	Maximum number of consecutive frost days	Longest period of consecutive days when TN < 0°C, where TN is the daily minimum temperature. This indicator is used as a general frost damage indicator.	Day
CSU	Maximum number of consecutive summer days	Longest period of consecutive days when TX > 25°C, where TX is the daily maximum temperature. This indicator provides information on drought stress or on optimal growth for C4 crops (crops that use the C4 carbon fixation pathway, e.g. maize).	Day
CWD	Maximum number of wet days	Maximum number of consecutive wet days	Days
GSL	Growing season length	Number of days between the first occurrence after 1st January (1st July in southern hemisphere) of at least 6 consecutive days with TG > 5°C and the first occurrence after 1st July (1st January in southern hemisphere) of at least 6 consecutive days with TG < 5°C, where TG is the daily mean temperature.	Days
TNn	Minimum of daily minimum temperature	Minimum value of TN over 10 days, where TN is the daily minimum temperature. This indicator provides information on long-term climate variability and change.	K