Scenario-based and Scenario-neutral Climate Change impacts assessment analysis on Muzza District's agriculture

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Abstract - The study aims to evaluate the effects of climate change, specifically in terms of temperature and precipitation variations, on the agricultural region of Muzza District, which primarily cultivates maize. The assessment is conducted with two methods: the top-down approach, which utilizes official IPCC projections downscaled, obtained through global circulation models, and the bottom-up approach, which involves creating self-generated scenarios of temperature and precipitation alterations at the local level. Both methods evaluate the system through the quantification of the annual yield, revealing a decrease due to climate change. The second approach allows for an analysis of the adaptive capacity of the system by utilizing various crop patterns and assessing system performance in comparison to a fixed failure threshold. The results suggest that the best adaptive capacity for the region is a switch to soybean or tomato cultivation.

I. Introduction

The burning of fossil fuels and widespread deforestation over the last few centuries have caused elevated atmospheric Greenhouse Gas (GHG) concentrations, and these changes in GHG have resulted in significant climate shifts globally. Climate change has already warmed the planet: from the preindustrial period (1850–1900) to the present (2011–2020), the global average temperature over land has increased by 1.1°C [*IPCC AR6, 2021]*. This increased global temperature has led to a rise in the number of hot days and nights, and a fall in the number of cold days and nights [*Orlowsky et al.*, 2012], as well as changes in the frequency and severity of extreme weather events such as drought [*Spinoni et al.*, 2019] and precipitation events [*Fischer et al.*, 2013]. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate [*IPCC AR6, 2021]*.
Therefore, climate change is a global problem and as such is affecting and is going to affect more and more in the future all the aspects of human life, starting from the way in which human beings live and survive: food supply, which means agriculture production, a sector considered particularly vulnerable for relying necessarily on water content, that is going to change very much in the future because of temperature and precipitation fluctuations [*Bocchiola et al.*, 2013]. To meet projected growth in human population and per-capita food demand [*Gerland et al.*, 2014], agricultural production will significantly expand in the coming decades, mostly through irrigated crops, inducing a considerable rise in water demand [*Sauer et al.*, 2010]. On the other hand, water availability, which is often a key factor in determining crop productivity [*Siebert and Döll*, 2010], is projected to decrease in many regions due to climate change impacts [*Gornall et al.*, 2010]. For each degree of global temperature increase, wheat yields are expected to reduce by 4–6% [*Liu et al*, 2016], increases in temperature are expected to similarly impact maize productivity and by the end of the century the areas producing 56% of the world's maize are predicted to experience a decline in yield [*Zhao et al.*,2017]. So, for these reasons, there is an urgent need for agriculture to adapt to ensure future food security. Adaptation strategies such as changing land and cropping practices, developing improved crop varieties, improving irrigation systems, changing food consumption and waste can help build resilience in the agriculture sector and ensure future food security.
In this paper the analysis is focused on the Muzza irrigation district, one of the largest agricultural areas in Lombardy, known for its importance in terms of food security and production in Europe. Therefore, it is crucial to analyse the impacts that this region will face in the coming decades due to climate change. The objective is to simulate future projections and scenarios in the most possible accurate way to support decision-making and adaptation initiatives.
There are two approaches that can be used to assess the impacts of climate change on future systems. The first approach is the Scenario-based or Top-down approach, which relies on official scenarios, i.e. those provided by the Intergovernmental Panel on Climate Change (IPCC). These scenarios are used to obtain future trajectories of climate variables such as temperature and precipitation through the simulation of global circulation models (GCM). However, these results need to be downscaled to the regional scale to determine local impacts on various sectors. While this approach benefits from official projections, it is affected by the "expansion of uncertainty" as uncertainty propagates through every step of the assessment from global scenarios to local impacts. The second approach is the Scenario-neutral or Bottom-Up approach, which has gained popularity recently due to its ability to better understand uncertainty. This method consists in moving from the local to the global scale, generating self-made regional scenarios in the exposure space. These scenarios are then used to test the performance of the system in various situations, identifying a failure boundary as the starting point for adaptive solutions. This approach still requires global

scenarios and trajectories properly downscaled and adjusted at the same spatial resolution for comparison with the synthetic-generated scenarios to acquire information on the time component and on the transient. It also gives insights into the maximum adaptive capacity of the system.
This paper aims to present the results of both climate assessments conducted using these two approaches. The focus is on assessing the impacts of climate change in the Muzza agricultural district and providing hints for adaptive solutions. The assessments cover three different time periods (2001-2010, 2051-2060, 2091-2100) and consider three IPCC future global scenarios defined in the 2021 Assessment Report n.6: SSP1-2.6, SSP3-7.0, and SSP5-8.5.

II. Material and Methods

Scenario-based approach

A. Global trajectories

The scenario-based approach is the first method used to assess the impacts of climate change on the Muzza agricultural District. It consists in relying on official IPCC scenarios to obtain future temperature and precipitation trajectories through GCM simulations, then the trajectories are downscaled to a regional scale and the impacts are determined at the local scale through an impact model, using a top-down working scheme.
The temperature and precipitation trajectories were downloaded from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) site. ISIMIP is an international network of climate-impact modellers that aims to provide comprehensive and consistent climate impact modelling under different scenarios. These trajectories are stored as NetCDF files, a data format that organizes the time series of climatic variables in 10-year blocks and a spatial domain with a resolution specific to the climate model used. The climate model used to generate these trajectories is MPI-ESM, a global climate model that incorporates sub-models of the atmosphere, ocean, terrestrial biosphere, and ocean biogeochemistry. The trajectories contain daily data of temperature and precipitation for each 10-year period and for all cells in the domain, which has a size of 360 x 720 (latitude x longitude).

Three specific periods were chosen for the analysis:
- 2001-2010: the historical period, which is used for comparison and as reference in the downscaling procedure and in the evaluation of the impacts;
- 2051-2060: the middle-of-the-century period, selected to provide insights into future projections and impacts when global carbon and climate neutrality goals are expected to be met;
- 2091-2100: the end-of-the-century period.

Whereas the three IPCC scenarios considered are:
- SSP1-2.6: it assumes that CO_2 emissions are severely cut reaching net-zero after 2050 and as result temperatures are projected to stabilize around 1.8 °C higher by the end of the century;
- SSP3-7.0: it assumes that CO_2 emissions roughly double from current levels by 2100 and average temperatures are projected to rise by 3.6°C;
- SSP5-8.5: it represents the worst-case scenario considered, it assumes that the current CO_2 emissions double by 2050 and the average global temperatures rise by more than 4.4°C by 2100.

B. Downscaling

Downscaling is a technique used to obtain higher resolution climate model outputs that can better capture local impacts. In this case, since the spatial resolution of the global trajectories is 50 km x 50 km, which is too coarse to evaluate the local impacts, it is necessary to downscale the trajectories to a higher resolution of 250 m x 250 m to have more dense values of temperature and precipitation. One possible approach to downscaling is the use of statistical methods. The specific statistical method adopted in this study is called Quantile Mapping, it was used to identify the statistical relationship between the outputs of the global climate model and the local observations. This statistical relationship was then used as a function to correct the bias between model outputs and observations to obtain the correct future trajectories. This method involves matching the cumulative density function (CDF) of the model outputs during a control period with the CDF of local observations. This matching process generates a quantile-quantile correction function, which can be used to remove any biases and correct the entire distribution of future projections.

Scenario-Neutral approach

A. Historical trajectories to perturb.

The impacts of climate change on the Muzza District region and the adaptive capacity of the system can be assessed also using a second method: the Scenario-Neutral approach, or Bottom-Up. It consists in generating different self-made scenarios by perturbing the historical trajectories, obtaining trajectories which are not linked to a specific time period. The first step regards the selection of the historical scenario to perturb, in order to generate the so-called exposure space. The historical daily trajectories of observations of temperature and precipitation from 1993 to 2007 were given and used to find a representative year whose trajectories could be perturbed. The choice operated in this report is to select the initial year contained in the historical period (2001-2010) considered in the Top-Down approach, since it appears an average-trending year both for temperature and precipitation, so the daily trajectories of 2001 are the one that will be perturbed. In Fig.1 is possible to see the yearly average values of temperature and precipitation for the years considered.

B. Self-generated scenarios

Once got the historical trajectories, the perturbation can be applied following two different approaches: the additive perturbation and the multiplicative perturbation, whose equations are reported in (1.1) and (1.2).

$$\theta_P = \theta_H + \gamma \quad (1.1)$$

$$\theta_P = \theta_H \times \gamma \quad (1.2)$$

Where θ_P are the projected trajectories and θ_H the historical ones, while the perturbation factor is $\gamma \in [\gamma_m, \gamma_M]$, where $\gamma_m \leq 0 \leq \gamma_M$. The generated scenarios depend on the number of the perturbation factors γ applied.

In this paper the following setting are selected:

1. additive perturbation applied to temperature. Specifically, the range for the perturbation factor has been set as the following: [-2°C;8°C], with a step of 1°C, to have a plausible and as wide as possible range. The range considered is deliberately asymmetrical because all IPCC official scenarios agree in predicting an increase in temperatures compared to the current ones, consequently more weight has been given to the positive γ. It goes up to a potential increase of 8°C in temperature, which overtakes even the most extreme scenarios that are considered in the IPCC projections, where is expected a maximum increase of almost 6°C. By setting a wider range, also in the lower extreme, the analysis aims to account for a broader range of potential outcomes and ensure a more comprehensive assessment of the possible impacts of climate change.
2. multiplicative perturbation applied to precipitation. In this case the range is set equal to [0.7;1.3] with a step of *0.06. This range is selected symmetric with respect to the initial condition due to the uncertainty in the prevision. Perturbing the precipitation multiplicatively allow us to avoid the generation of negative values, as is not physically feasible to have a negative value of precipitation.

Using this ranges, we can generate a high number of scenarios. This allows us to better explore the uncertainty related to the future projections, without having an excessive computational cost.

C. Failure boundary

From the set of generated scenarios, a simulation is then computed through AquaCrop model in order to obtain the system performance in each condition. In the exposure space, obtained from the perturbation of the historical trajectories, is then possible to define the failure boundary, which is a combination of temperature and precipitation giving a performance of the system not considered acceptable by the stakeholders. The selection of this value has been obtained by evaluation of the annual yield in the historical years, visible in Fig. 2, and by choosing of a non-satisfactory year: it's the case of 2005, whose cumulative maize yield at the end of the year was less than 7 tons. With respect to this threshold, the generated scenarios will then be categorized in success or failure ones.

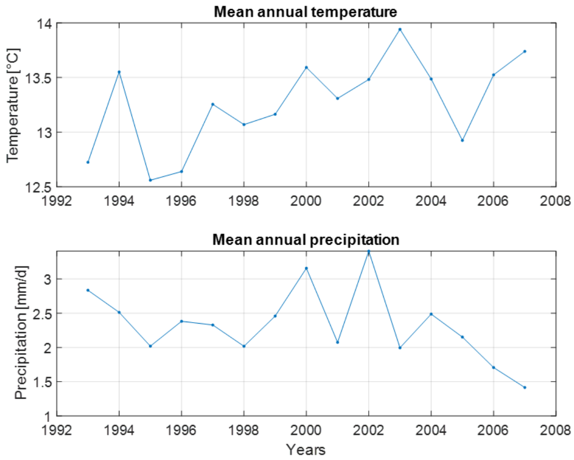

Figure 1 - Annual mean observation of temperature and precipitation in the period from 1993 to 2007.

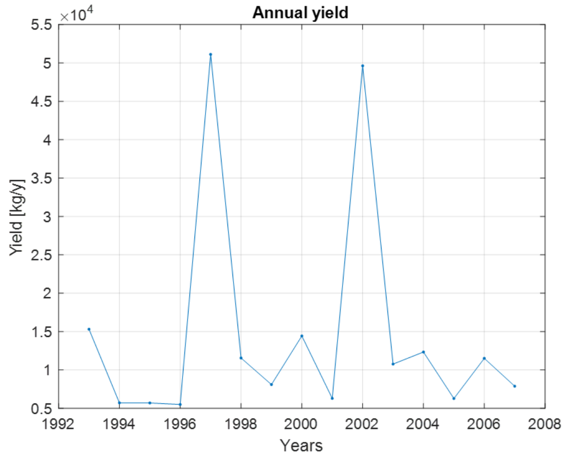

Figure 2 - Annual yield [kg/y] in the period from 1993 to 2007.

D. Adaptive capacity

The following step is to explore the adaptive capacity of the system, in order to optimize the system performance for each climate condition. The adaptation strategies considered regard the change of crop: in the following paragraphs the convenience to switch the crop type will be explored for each scenario, to obtain, when possible, a higher level of performance for the system, in term of total revenue. In the already cited IPCC AR6 it's pointed out how crop diversification seems to reduce crop sensitivity to precipitation variability, yield losses and crop insurance pay-outs under drought [IPCC AR6, 2021]. In Table 1 are reported the different crop types and the unit of revenue for each one, the comparison of different crops must be held on an economic base [€/y] and is not possible on a yield [kg/y] one, having them a different yield per hectare rate.

Table 1 - Price [€/100kg] of different crop types.

Crop	Price [€/100 kg]
Maize	14
Rice	30
Tomato	8
Soybean	24.5
Grass	9.3

Using the data provided by this Table is also possible to convert the yield corresponding to the failure threshold in monetary term, obtaining an expected revenue of almost 880 €/y.

Common setting for the two approaches

A. Local District

The Muzza region is an agricultural zone located East of Milano, with an extension of 700 km^2, approximately between the Adda and the Po river. This region is particularly fertile, with a maize production of 75%, an occupation for almost the 20% of temporary grassland and a residual production of tomato, rice and soybean. Since the computational capability of the calculator used is limited, in this paper just one cell of the domain has been considered in order to extract the observations of the cell needed to perform the downscaling and the features to calculate the yield; precisely, the domain is composed of 11667 cells and in this work the cell number 720 has been considered.

B. Impact Model

The IPCC and the self-generated scenarios are then used to feed the impact model AquaCrop. AquaCrop is a crop growth model developed by the Land and Water Division of Food and Agricultural organization of the United Nations (FAO) to address food security and to assess the effect of environment and management on crop production. AquaCrop simulates yield response to water of herbaceous crops and is particularly suited to address conditions where water is a key limiting factor in crop production. The model is composed of three different boxes: crop growth simulation, which returns the growth stage; this influences the water balance simulation, which generates transpiration; transpiration affects the crop biomass and yield, which is the output of interest. As an input, the model takes the trajectories of temperature and precipitation. This model is used in the paper to find ultimately the yield production under different scenarios of temperature and precipitation.

III. Results and Discussion

A. Global trajectories

To provide a concise representation and comparison of the global projections, it would be helpful to calculate the average values for each trajectory over the ten-year period and present the results using a colormap. This means that each trajectory will be represented by a single value, which is the mean, for each spatial cell. The outcomes of this calculation are illustrated in Fig. 3 for temperature projections in each scenario, and in Fig. 4 for precipitation projections in the same scenarios.

The analysis shows an overall increase in the temperature trend of the future projections, although the growth varies depending on the scenario: the SSP1-2.6 scenario registered the minor increase while the SSP5-8.5 scenario the greatest one.

The analysis of precipitation does not show significant differences between scenarios and temporal periods, except for a slight increase over time. However, this result is highly predictable because climate change is expected to alter mainly the distribution of precipitation when it comes to frequency and intensity of extremes events. These are alternated with periods of drought, resulting in a smoothing effect when summing up for the entire period considered.

As can be seen from Fig. 3, the Mediterranean region is a climate change hotspot, it has warmed and will continue to warm more than the global average, particularly in summer. The region will become drier due to the combined effect of decreased precipitation and increased evapotranspiration. At the same time, extreme precipitation will increase in some areas. [IPCC AR6, 2021]. Regarding Italy, in the centre of the Mediterranean region, the trends are confirmed and in general a warmer and dyer climate is expected in the future projections.

Fig. 5,6,7 also include the graph of the temperature Deltas for each scenario, which represents the difference between the average temperature values in two periods. The first Delta graph depicts the difference between the historical and mid-term periods, while the second Delta graph shows the difference between the long-term and mid-term periods.

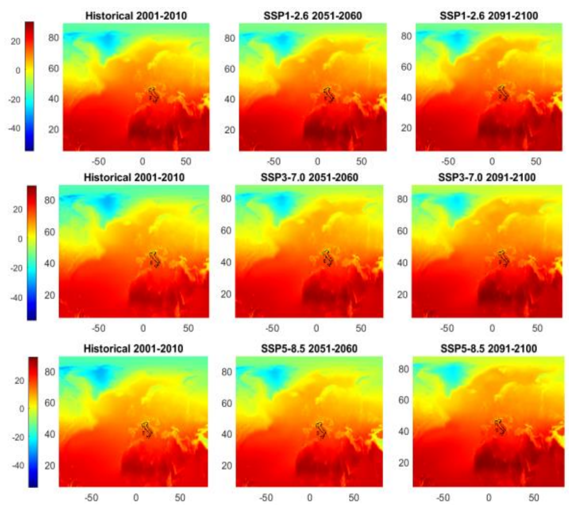

Figure 3 - Average historical temperature (2001-2010) and future projections of temperatures in °C for each period (2051-2060,2091-2100) and for each scenario (SSP1-2.6, SSP3-7.0, SSP5-8.5) considered.

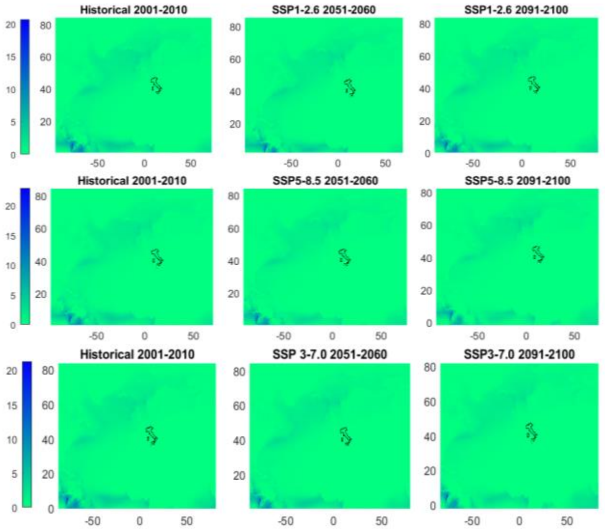

Figure 4 - Average historical precipitation (2001-2010) and future projections of precipitation in mm/d for each period (2051-2060,2091-2100) and for each scenario (SSP1-2.6, SSP3-7.0, SSP5-8.5) considered.

The spatial variations in the rate of warming are noteworthy, with a more intense warming observed in the northern regions. Additionally, the rate of change differs between the two periods for all scenarios. Generally, in the SSP1-2.6 and SSP3-7.0 scenarios, the rate of warming slows down, while in the SSP5-8.5 scenario, it intensifies. These differences correspond to the varying levels of effort assumed by the IPCC in each scenario for reducing emissions.

Furthermore, both the SSP3-7.0 and SSP5-8.5 scenarios highlight Italy as one of the regions experiencing the most intense climate change. This emphasizes Italy's high vulnerability to the effects of climate change.

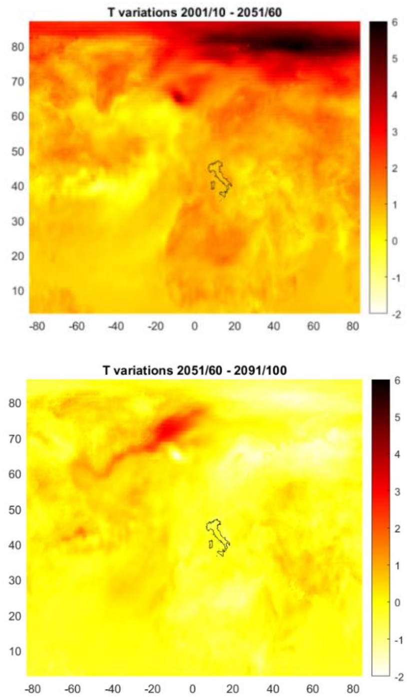

Figure 5 - Temperature Deltas in °C between the historical period and the middle of the century, and between the middle of the century and the end of the century for scenario SSP1-2.6.

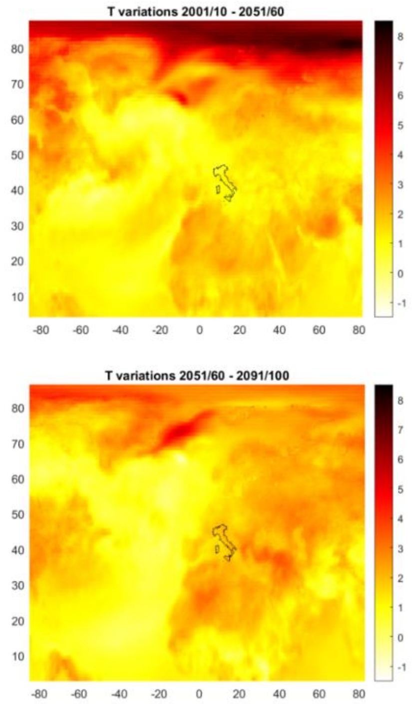

Figure 6 - Temperature Deltas in °C between the historical period and the middle of the century, and between the middle of the century and the end of the century for scenario SSP3-7.0.

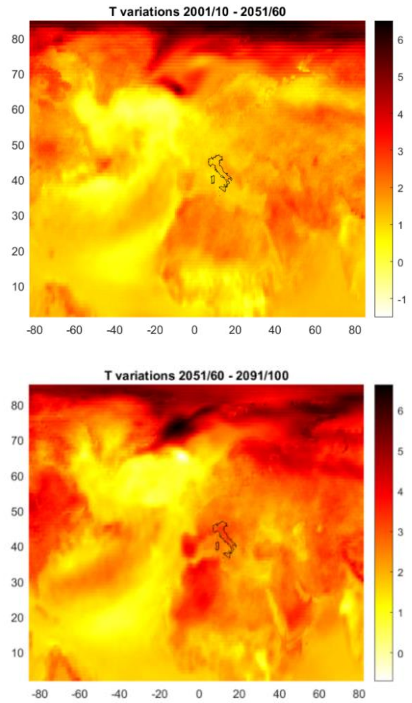

Figure 7 - Temperature Deltas in °C between the historical period and the middle of the century, and between the middle of the century and the end of the century for scenario SSP5-8.5.

B. Downscaling

The Quantile Mapping Downscaling method has been utilized on all future temperature and precipitation projections for all three scenarios and time periods to obtain the local projections for the Muzza District. This involves transitioning from a spatial resolution of 50 km x 50 km (resolution used by GCM) to a finer resolution of 250 m x 250 m. Fig. 8, 9, 10, 11, 12, and 13 display the comparison between different trajectories, including observations, modelled trajectories for the control period, and projected trajectories for both the global (pre-downscaling) and local scales (post-downscaling), for each scenario and time period.

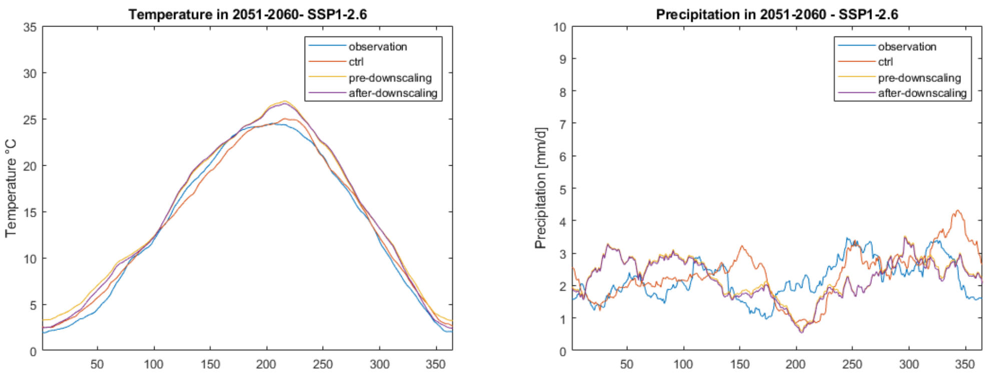

Figure 8 - Comparison of temperature and precipitation trajectories pre and post downscaling for SSP1-2.6 scenario for the period 2051-2060.

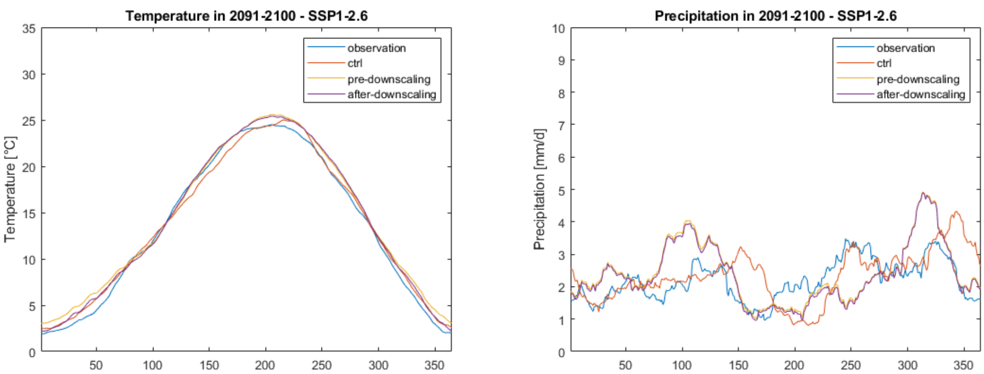

Figure 9 - Comparison of temperature and precipitation trajectories pre and post downscaling for SSP1-2.6 scenario for the period 2091-2100.

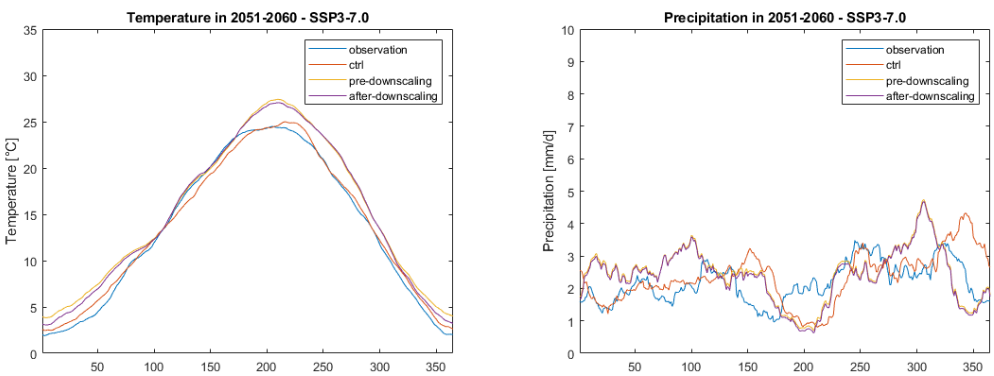

Figure 10 - Comparison of temperature and precipitation trajectories pre and post downscaling for SSP3-7.0 scenario for the period 2051-2060.

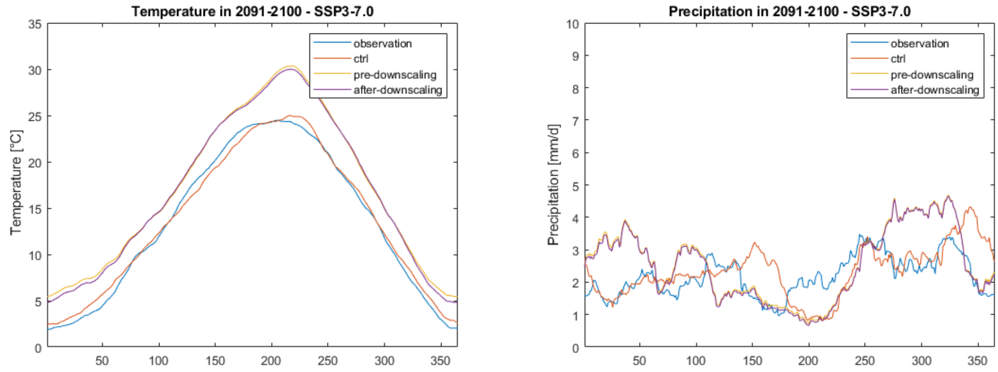

Figure 11 - Comparison of temperature and precipitation trajectories pre and post downscaling for SSP3-7.0 scenario for the period 2901-2100.

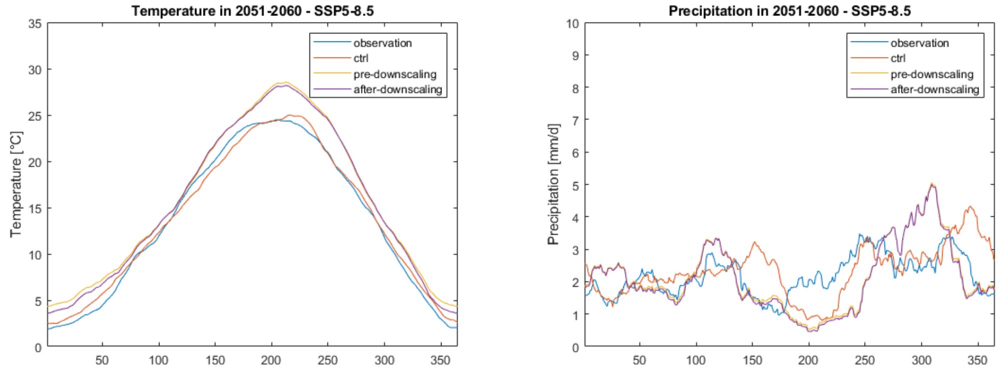

Figure 12 - Comparison of temperature and precipitation trajectories pre and post downscaling for SSP5-8.5 scenario for the period 2051-2060.

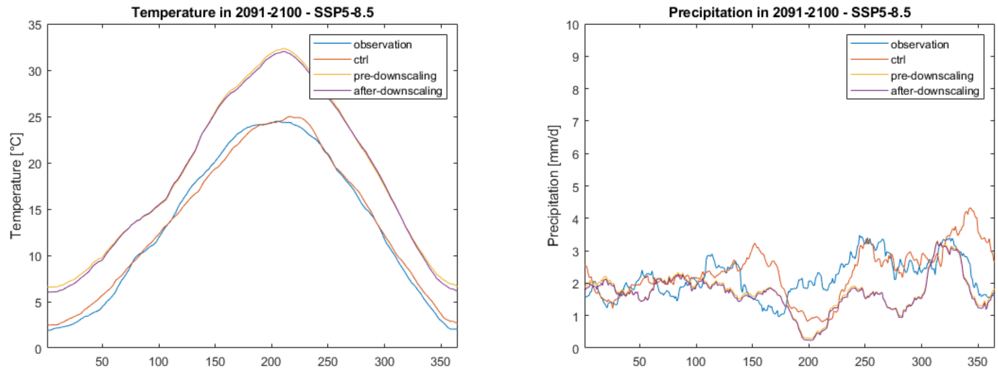

Figure 13 - Comparison of temperature and precipitation trajectories pre and post downscaling for SSP5-8.5 scenario for the period 2091-2100.

The pre-downscaling and post-downscaling trajectories are similar but it can be seen that in the colder months of the year, the downscaled trajectories for temperature are lower than the trajectories at the global scale. This suggests that the region under investigation experiences harsher winters compared to what is predicted by the global-scale simulations.

Regarding precipitation, the downscaled trajectories are lower than the global ones, particularly in June and July. This indicates that the region is drier than the global mean during these months.

In general, the global trajectories smooth out all seasonal peaks in the spatial domain, whereas the local trajectories reflect the typical seasonal characteristics of the region of interest.

C. *Impacts estimation*

Finally, Fig. 14, 15, 16, 17, 18, 19 report the average annual yield of maize calculated for each scenario (SSP1-2.6, SSP3-7.0, SSP5-8.5) and each period (2001-2010, 2051-2060, 2091-2100) considered, at the local scale, i.e. using the downscaling trajectories which give the performance of the Muzza District. These results have been obtained, as already introduced, through AquaCrop simulation. In order to explain the yield results there are also reported the trajectories of mean temperature and precipitation during the selected periods.

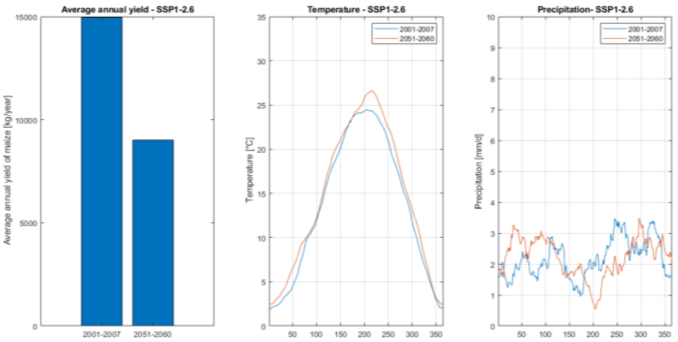

Figure 14 - Comparison between historical average annual yield and the one of scenario SSP1-2.6 for the period 2051-2060 and comparison between historical trajectories future trajectories of temperature and precipitation of scenario SSP1-2.6 for the period 2051-2060.

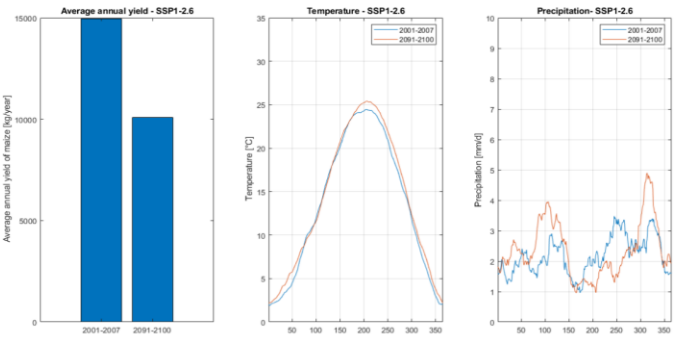

Figure 15 - Comparison between historical average annual yield and the one of scenario SSP1-2.6 for the period 2091-2100 and comparison between historical trajectories future trajectories of temperature and precipitation of scenario SSP1-2.6 for the period 2091-2100.

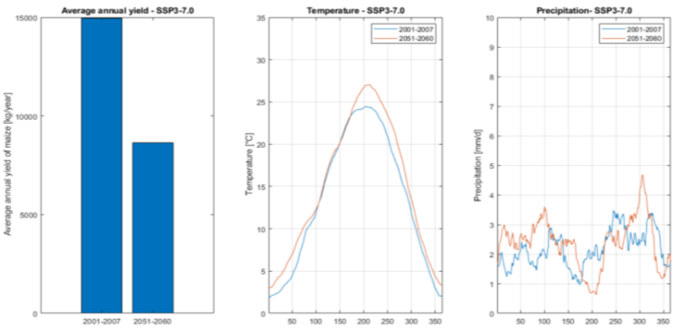

Figure 16 - Comparison between historical average annual yield and the one of scenario SSP3-7.0 for the period 2051-2060 and comparison between historical trajectories future trajectories of temperature and precipitation of scenario SSP3-7.0 for the period 2051-2060.

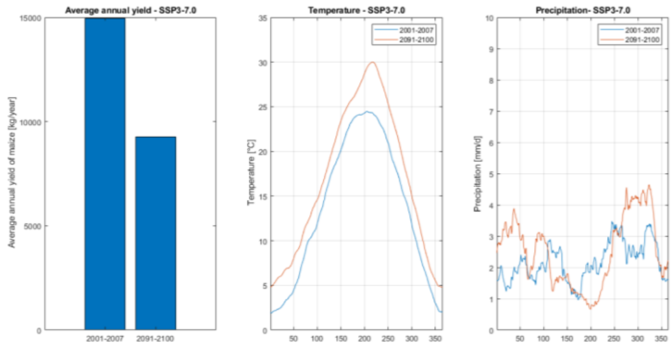

Figure 17- Comparison between historical average annual yield and the one of scenario SSP3-7.0 for the period 2091-2100 and comparison between historical trajectories future trajectories of temperature and precipitation of scenario SSP3-7.0 for the period 2091-2100.

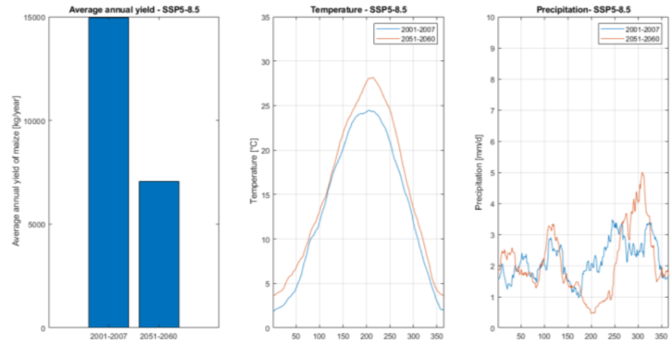

Figure 18 - Comparison between historical average annual yield and the one of scenario SSP5-8.5 for the period 2051-2060 and comparison between historical trajectories future trajectories of temperature and precipitation of scenario SSP5-8.5 for the period 2051-2060.

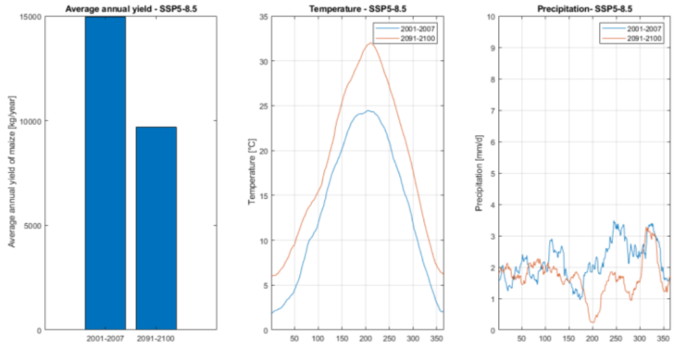

Figure 19 - Comparison between historical average annual yield and the one of scenario SSP5-8.5 for the period 2091-2100 and comparison between historical trajectories future trajectories of temperature and precipitation of scenario SSP5-8.5 for the period 2091-2100.

Firstly, all the graphs show that the average future yield is consistently lower than the historical average yield in every scenario and over all time periods considered. This is in line with the general expectations outlined in the official IPCC assessments, which point to a decline in maize production and emphasise that agriculture will be one of the sectors most affected by climate change.

This reduction in yield can be attributed to rising temperatures, particularly during the summer months, which lead to increased evapotranspiration and reduced rainfall when maize requires more water. It is worth noticing that May, June, and July are critical months for maize crops in terms of water availability.

Fig. 20 illustrates the comparison between average historical yield and the expected average future yields for three different future scenarios in the medium term and at the end of the century. Regardless of the scenario considered, the yield in the period 2051-2060 are consistently lower than the yields at the end of the century.

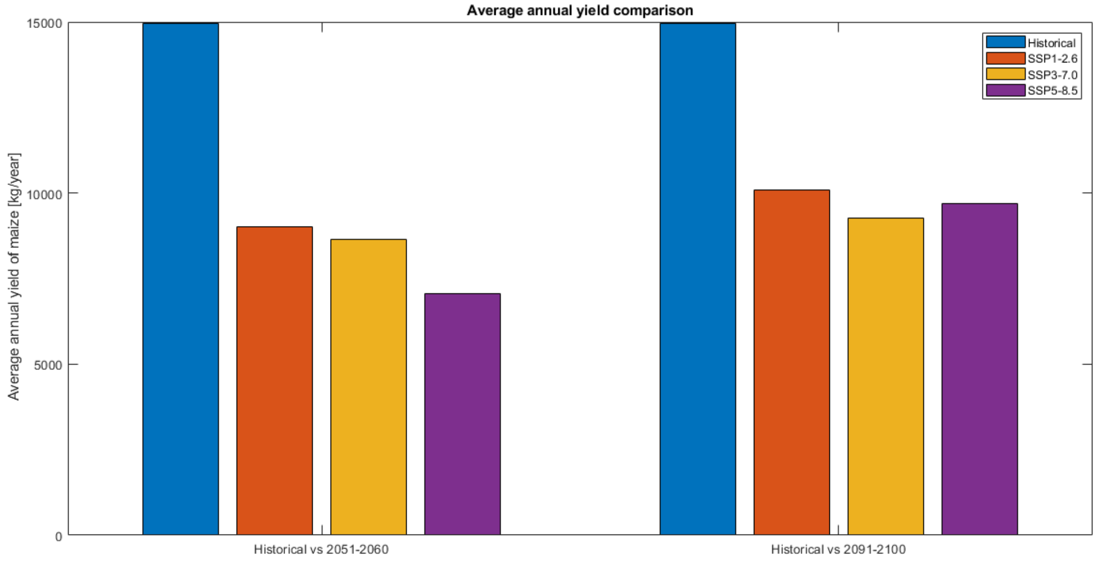

Figure 20 - Comparison of mean annual yield in three periods (2001-2010, 2051-2060, 2091-2100) in the SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenarios.

In the SSP1-2.6 scenario, this pattern can be explained by the fact that the emissions peak is reached in the middle of the century, resulting in a slower increase in temperature trends in the second half of the century. Consequently, as depicted in Fig. 14 and 15, the period 2051-2060 is characterised by higher average temperatures compared to the 10 years before the century's end, accompanied by a higher average precipitation. These favourable conditions contribute to an increase in the maize production.
In the case of the SSP3-7.0 scenario, despite higher average temperatures at the end of the century, Fig. 16 and 17 illustrate a different precipitation distribution between the two periods. Specifically, there is a tendency for greater winter rainfall at the century's end than in the middle of the century, potentially leading to a more favourable water distribution.

Looking at the SSP5-8.5 scenario and comparing the graphs (Fig. 18 and 19), it is noticeable that the period 2051-2060 has higher average temperatures and a greater quantity of rainfall on average. However, further investigation is required to comprehend why, despite the seemingly unfavourable conditions, the yield is higher at the century's end. This answer can be derived by analysing the evolution of the individual annual yields throughout the period 2091-2100 (Fig. 21), where it can be seen that 2093 is a particularly profitable year, which is why this year influences the average yield by increasing it.

Scenario-neutral approach

A. Historical trajectories to perturb.

The perturbed trajectories obtained with the multiplicative and additive methods respectively are reported in Fig. 22 and 23.

As expected, the generated trajectories for precipitation do not include negative values, while the temperature ones do: this is coherent with the physical nature of the two variables.

B. Adaptive Capacity

Finally, the Bottom-Up or Scenario Neutral approach, has been implemented, to obtain the system performance under self-generated future climate scenarios, together with the improvement given by adaptive responses. Fig. 24 and 25 report the classification of the scenarios in failure or success ones with respect to the failure boundary set and the system performance in terms of annual revenue for the scenarios generated and described above, for the case of maize.

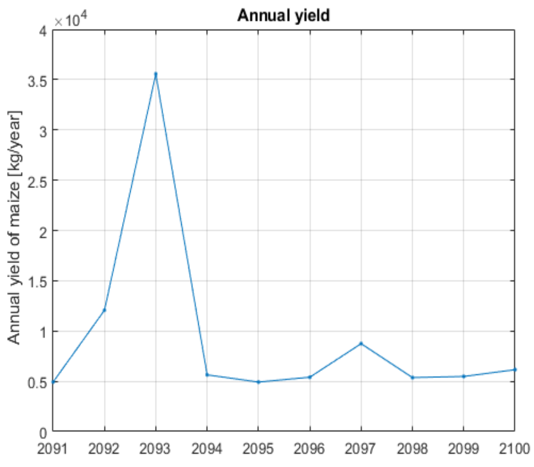

Figure 21 - Annual yield [kg/y] from 2091 to 2100 for SSP5-8.5 scenario.

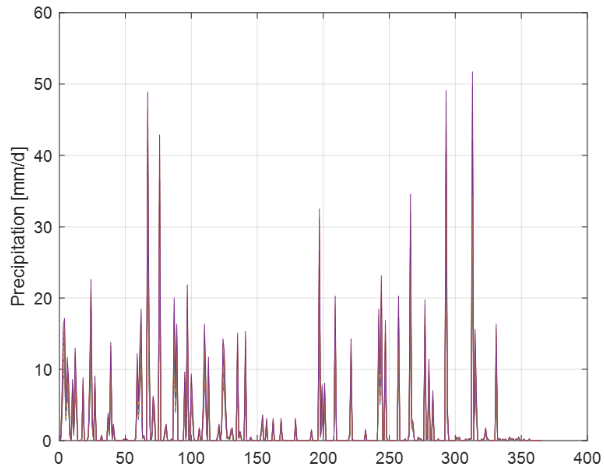

Figure 22- Perturbated trajectories of precipitation obtained through multiplicative perturbation of the historical trajectories of 2001.

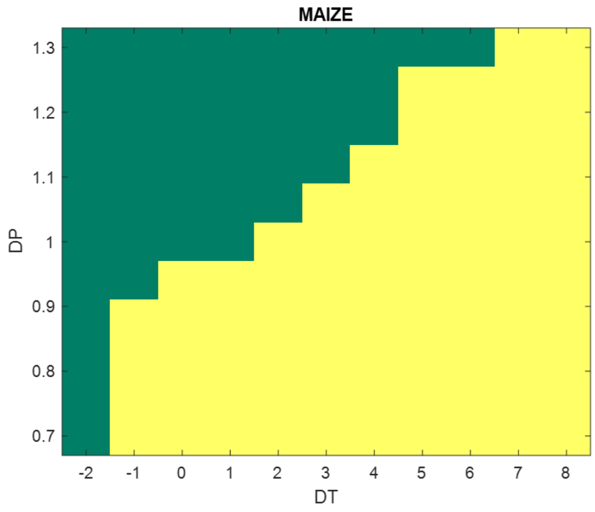

Figure 24 - Binary partitioning of the exposure space in failure (yellow) and success (green) by comparison of the annual yield of maize with the fixed failure threshold.

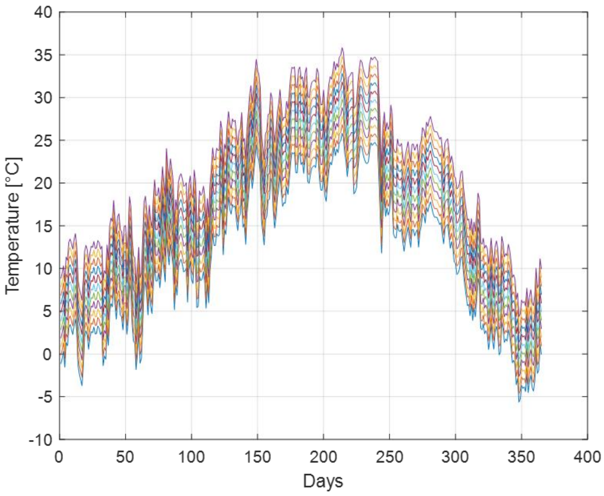

Figure 23 - Perturbated trajectories of temperature obtained through additive perturbation of the historical trajectories of 2001.

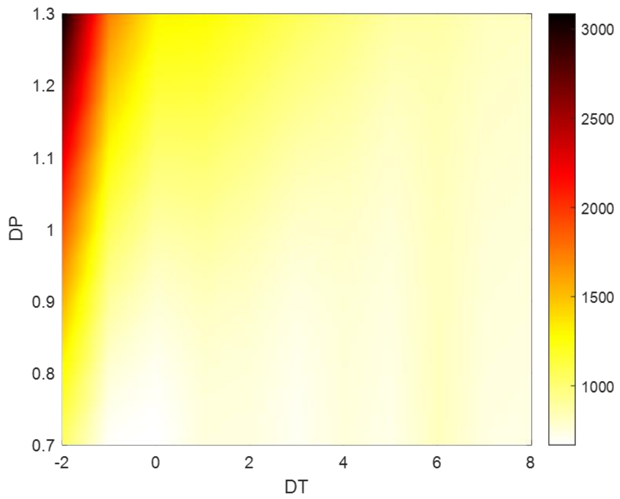

Figure 25 - Exposure space in terms of revenue [€/y] for the generated scenarios.

Looking at Fig. 24 some considerations can be made. The failure boundary shows a diagonal tendency, except for extremes, that means that the increasing of temperature can be compensated by an increasing in the precipitation, and vice versa; on the other ways on the extremes there is a different behaviour, where for the highest temperature the system fails for each precipitation value, while for the lowest precipitation, with a considerable temperature reduction it can be achieve a successful performance. The actual condition, 0 for additive perturbation and 1 for multiplicative one, correspond to a successful scenario, if the temperature increases by more than 2 °C without a corresponding increase in precipitation, the current situation would be considered a failure in terms of its performance.
Looking at the Fig. 25, we can see that the peak in revenue is found in correspondence of a high increase in precipitation and a decrease in temperature, with the slightest increase in the latter leading to a drastic decrease in revenue.

As an adaptive response, a crop change has been explored: in particular, Fig. 26 reports the classification of the scenarios in failure and success ones, again on a revenue basis, for the case of rice. It’s easy to note how this crop type wouldn’t give any solution in terms of adaptation: indeed, there are no scenarios for which rice cultivation would assure a satisfying revenue with respect to the one assumed as failing for the case of maize. In this sense, the cultivation of rice for the Muzza District in the scenarios considered doesn’t seem to be a useful adaptive response to climate change.

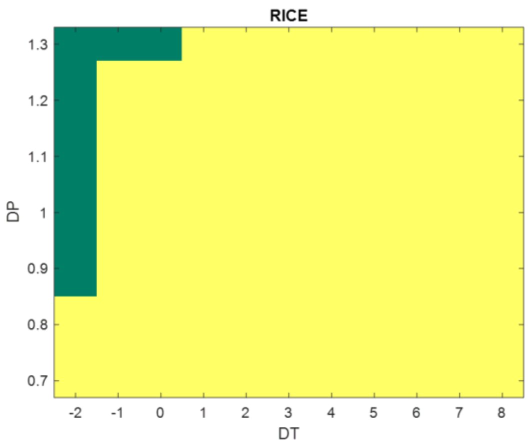

Figure 26 - Binary partitioning of the exposure space in failure (yellow) and success (green) by comparison of the annual yield of rice with the fixed failure threshold.

Very different is the case of soybean and tomato, reported in Fig. 27, for which all the scenarios considered show a success performance in terms of revenue with respect to the failure one calculated in the case of maize. Therefore, switching towards these two crops type, when maize doesn't perform well, can assure a satisfying adaptation strategy to the climate change expected in all the future scenarios generated.

Fig. 28 reports the system performance in term of revenue for respectively soybean and tomato. Every scenario assures a revenue higher than the one corresponding to the failure threshold, 880€, but there are significative differences between the performance of the two crops. Indeed, tomato consistently outperforms soybean in terms of revenue generation, particularly in warmer scenario, while soybean shows more fragility in drier and warmer conditions.

A further case is the one involving the grass, where it can be clearly seen, in Fig. 29, that this crop is less sensitive to the increase of temperature than the maize, anyways the reduction of precipitation leads to a failure in almost every scenario.
The failure boundary obtained for maize and grass are different, the second appears to be successful in some scenarios in which the maize cultivation result in a failure, so it has been considered the case in which we switch from maize to grass, when maize fails, in order to verify what exposure space is obtained by considering both crops together (Fig. 30).

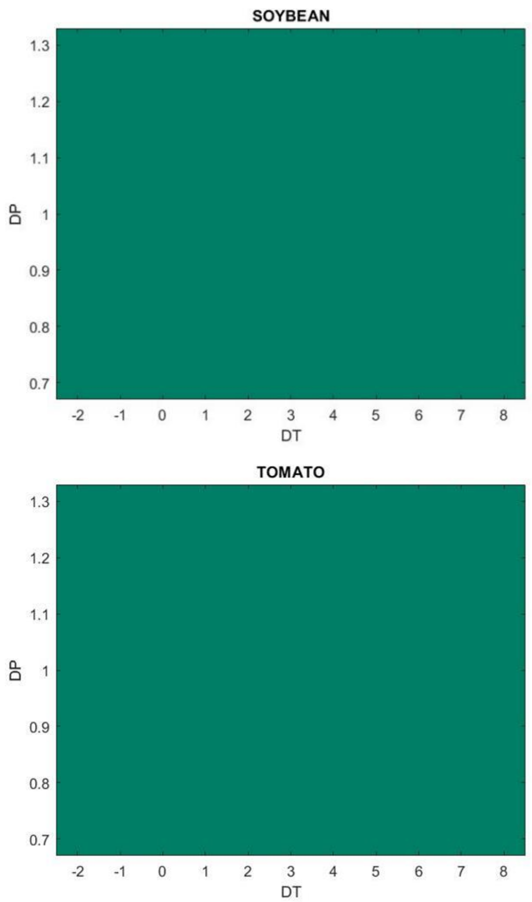

Figure 27 - Binary partitioning of the exposure space in failure (yellow) and success (green) by comparison of the annual yield of soybean and of tomato with the fixed failure threshold.

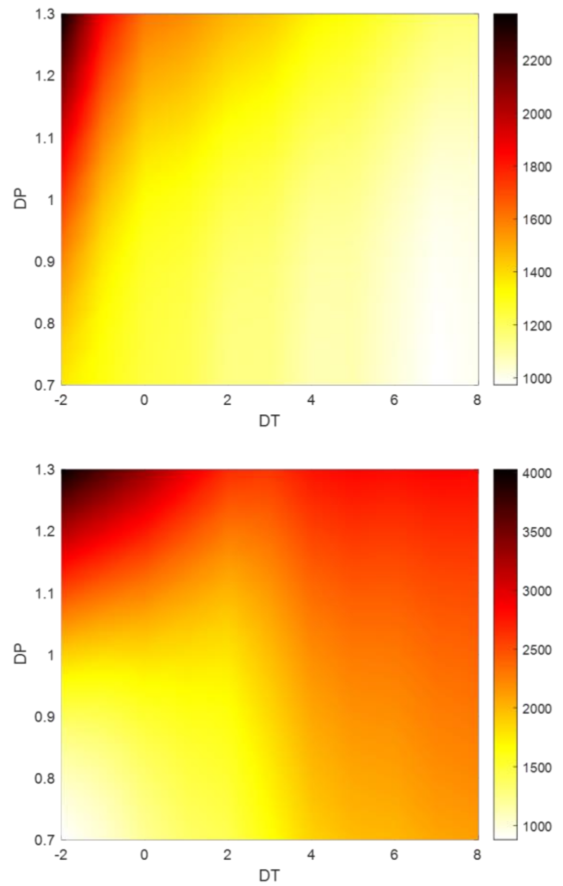

Figure 28 - Exposure space in terms of revenue [€/y] for the generated scenarios for soybean (above) and tomato (below).

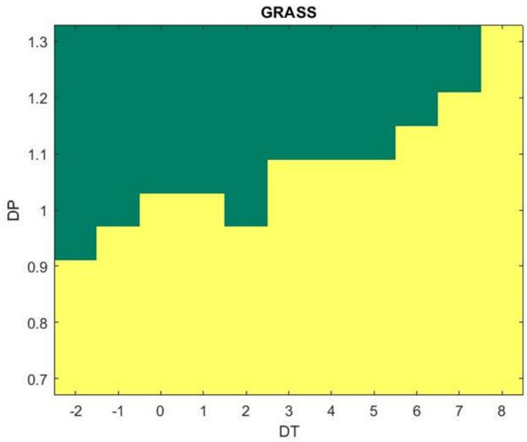

Figure 29 - Binary partitioning of the exposure space in failure (yellow) and success (green) by comparison of the annual yield of grass with the fixed failure threshold.

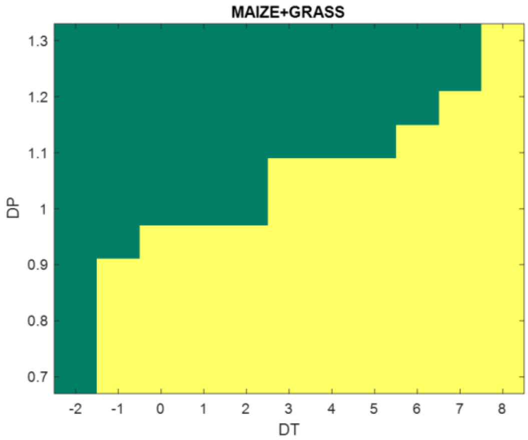

Figure 30 - Binary partitioning of the exposure space in failure (yellow) and success (green) by comparison of the annual yield of maize plus grass, when the maize fails, with the fixed failure threshold.

Finally, to validate the results and to obtain some information about the reaching time of the scenarios, the IPCC downscaled projections have been added to the map of the crops performance (Fig 31). This can be useful also to see the favourable direction of changing of both temperature and precipitation and to analyse how probable and far in time would be the scenarios requiring an adaptational response in terms of crop change. The maps shows that that the worrying conditions for maize cultivation would be the ones obtained with the worst official scenario (SSP5-8.5), in the long but also in the middle term; indeed, these are the scenarios facing an increasing of temperature without an increasing in the precipitation.
Then it appears that the rice leads to a failure of the system performance in every official projected IPCC scenario.
Instead, the tomato and the soybean show a stronger adaptation capacity as they can assure a satisfying revenue whatsoever the climatic projections. These two crops clearly outperform all the others in term of system performance and adaptation to climate change.
As for the grass the worrying conditions would be the ones obtained with the worst official scenario (SSP5-8.5) only in the long term. It can be also noted that switching from maize to grass also allows for a success in the SSP5-8.5 scenario in the medium term that would otherwise have been a failure with maize alone. This case could be more easily implemented to increase the adaptability of the system for specific scenarios without an excessive monetary cost, unlike a complete change to a soybean or tomato crop, which even though they are much more convenient in terms of revenue, require a greater investment to implement the crop change. Therefore, this solution could be a short-term adaptation strategy. While the switch to soybean or tomato could be a long-term adaptation strategy.
A final comment regards other adaptation options which can be assumed as response to climate change impacts over agriculture: these can imply the cultivation of new and improved crops, such as seed varieties resistant to droughts and floods, or the improvement of agricultural and technological practises, particularly regarding irrigation. Crop switching is certainly a good option, since it allows, where needed, to choose varieties requiring a less quantity of water and at the same time adapted to new timing of sowing and harvesting [IPCC AR6, 2021]. Surely, such a choice requires huge investments in terms of plants, machines, equipment and specialized workers; in this sense, the projections of the climate trajectories and the simulation of the impacts become even more important, letting farmers to organize optimally their investments during the transient for the best future adaptation.

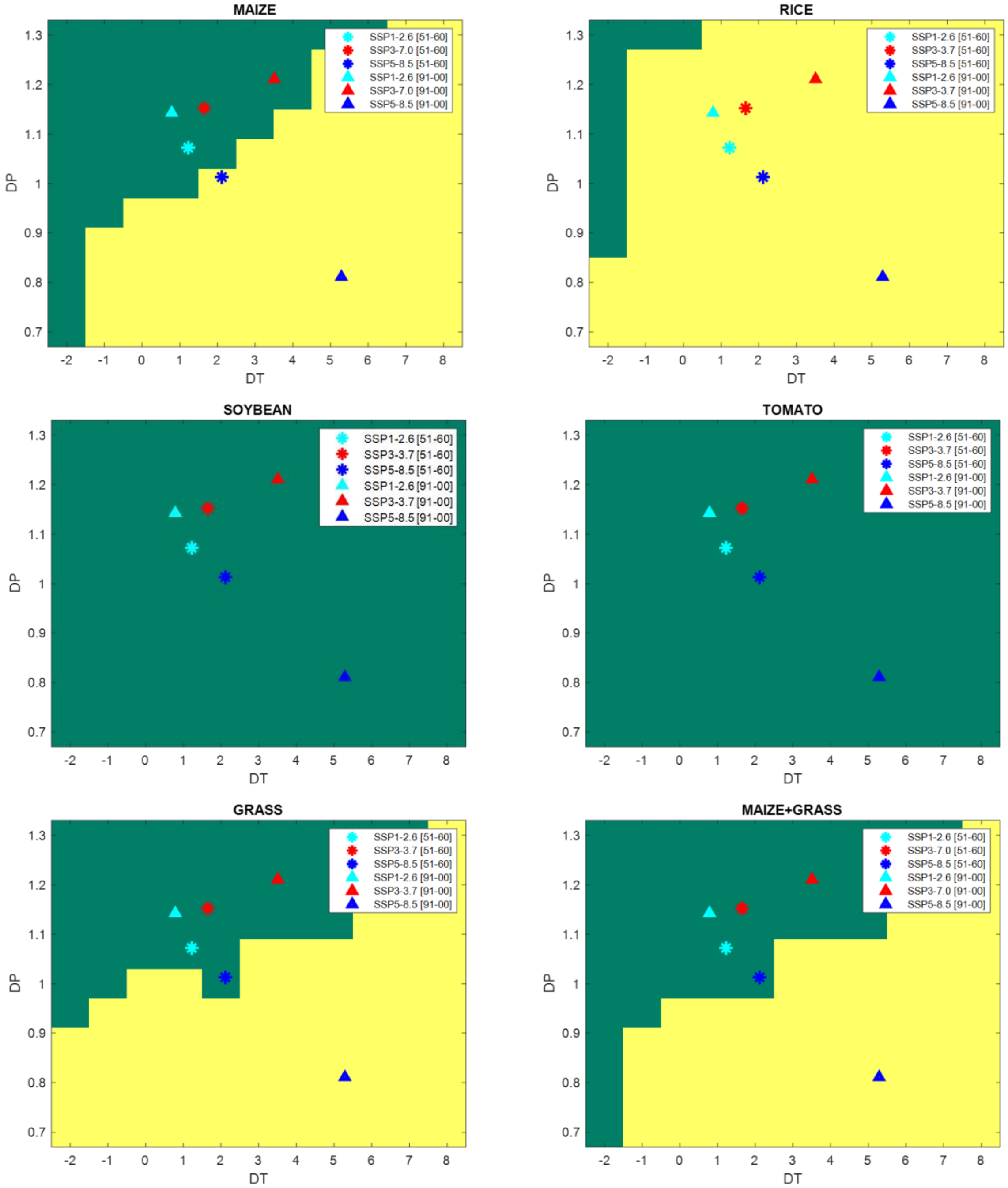

Figure 31 - Exposure space scenarios compared to IPCC's official projections SSP1-2.6, SSP3-7.0, SSP5-8.5 in the two period considered (2051-2060, 2091-2100) with the information about the performance of the system is terms of failure or success for all the crops.

IV. CONCLUSIONS

The expected impacts on the agricultural sector in the Muzza District have been analysed in this study, mainly in term of maize production, considering firstly different IPCC scenarios and then a larger set of self-generated ones. In this second case, also some adaptation options have been explored, in order to give farmers a possibility in terms of responses to climate change through crop switch.

For the first part of the analysis, three official IPCC scenarios have been considered, SSP1-2.6, SSP3-7.0, SSP5-8.5, in two different time periods, the middle-term 2051-2060 and the long-term 2091-2100. Through the downscaling operation it has been possible to obtain future trajectories of temperature and precipitation at the local scale in the considered periods and scenarios; as expected, the projections obtained show an increasing of temperature, while regarding precipitation, the region considered is drier than the global mean during the summer months. For these reasons the average future yield in each scenario and in each time period is expected to be lower than the historical one (1993-2007). Therefore, agriculture will be one of the sectors most affected by climate change.

The second part of the paper is focused on self-generated local scenarios, the results reported show that scenarios where temperature increases while the precipitation decreases are the most critical, in these cases, the maize production is going to decrease and to fall below a threshold of not-satisfaction. In addition, it has been assessed that the negative effects of climate change on agriculture strongly depend on the crop type, having tomato and soybean a satisfactory performance for all the scenarios considered; rice, on the contrary, is expected to perform worse in more scenarios than maize and grass finally, in combination with maize can be used to improve the adaptive capacity of the system in the short term. The comparison with the official IPCC projections, opportunely downscaled at the local dimension, indicates as worrying scenarios those compatible with a SSP5-8.5 pattern, with a decreasing of the performance in the long term. Again, also in these cases soybean and tomato can play a positive role and can be chosen as a well performative adaptation option.

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