Politecnico di Torino

Master's Degree in Environmental Engineering, Climate Change
A.a. 2023/2024

20th March 2024

Assessment of Climate Change Impact on Rainfed Barley Production in the Mediterranean Basin.

The Almeria province case study.

Relatori:
Luigia Brandimarte, KTH
Tiago Capela Lourenço, Universidade de Lisboa
Elena Comino, Politecnico di Torino

Candidato:
Francesco Saretto, s301511

“Per tutelare l’ambiente dobbiamo tutelare ogni uomo;
per tutelare ogni uomo dobbiamo proteggere il suo ambiente:
non ce lo aspettavamo, ma è questa vera pace.
E se ci arrivassimo per sbaglio, combattendo il riscaldamento globale?”
(Grammenos Mastrojeni, *L’arca di Noé,* 2014)

Summary

The Mediterranean basin is widely recognized as a climate change hotspot, with climate models projecting increasingly warmer and drier conditions that will impact local ecosystems, communities, and economies. Agriculture will be among the most affected sectors, with harsher conditions for crops' growth, greater water needs, and lower yields. One of the most resilient crops to limiting and stressful conditions is barley, which is often sown in areas where other crops and cereals would struggle. This work analyzed the impacts of climate change on rainfed barley using the province of Almeria as a case study. This is one of the most arid areas of the Mediterranean basin, where agriculture is among the main economic resources, and where barley is the main crop produced outside greenhouses. Barley growth was modeled using the AquaCrop model in its Python implementation, AquaCrop-OSPy. Setting the model up to avoid local re-calibration of the barley parameters and to capture multi-year trends in productivity change, rather than its interannual variability. The study focused on two 30-year time periods: mid-century (2041-2070), and end-century (2071-2100); and on *Shared Socioeconomic Pathways* scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5. For each time period and SSP scenario, the research also evaluated three sub-scenarios of soil water content at sowing: with the parameter set respectively at 10%, 20%, and 30% of the Total Available Water (the water present in the soil available for the crop to sustain its life). Having estimated climate change impact, the research analyzed different adaptation pathways (irrigation, the application of mulches, and the change in sowing date), to evaluate their performances for climate change adaptation in the area.

The results indicate the importance of soil water content for maintaining good yields, or reducing losses, and indicate the possible average yield change to be between +14% and -45% at mid-century, and between +12% and -55% at end-century. The greater variability in productivity is associated with the soil water content at sowing rather than on the SSP scenario, with SSP5-8.5 being the only one showing a marked difference compared to the others. Regarding irrigation, the results show how with a soil water content at sowing of 10% of the Total Available Water, irrigation up to 100 m^3/ha might not be sufficient to avoid productivity losses. Also, the study indicates that an optimal threshold to trigger irrigation for adaptation purposes might be found between 0% and 20% of the Total Available Water. Overall, it indicates how adaptation through irrigation can be viable in the province. The work moreover suggests the effectiveness of mulches as an adaptation strategy to partially limit irrigation water needs in the future and improve the yield performance of the crop. However, the research does not indicate a clear benefit linked to changing the sowing date to earlier or later sowing dates but suggests the importance of correctly seizing the sowing window to reach optimum yield in the future. Lastly, the work shows that the approach used to carry out this research is suitable to assess trends in yield change at multi-year scale, if the analyzed time window is indicatively larger or equal to 10 years, and if an error of around 10% on the results is accepted.

Keywords: *Barley, Rainfed, Climate Change, AquaCrop, AquaCrop-OSPy, Mediterranean, Climate Change Adaptation, Crop Modeling, Agriculture, Irrigation.*

Sammanfattning

Medelhavsområdet är allmänt erkänt som en hotspot för klimatförändringar, och klimatmodellerna förutspår allt varmare och torrare förhållanden som kommer att påverka lokala ekosystem, samhällen och ekonomier. Jordbruket kommer att vara en av de mest drabbade sektorerna, med tuffare förhållanden för grödornas tillväxt, större vattenbehov och lägre avkastning. En av de grödor som är mest motståndskraftiga mot begränsande och stressande förhållanden är korn, som ofta sås i områden där andra grödor och spannmål skulle ha svårt att klara sig. I det här arbetet analyserades klimatförändringarnas inverkan på regnkorn med provinsen Almeria som fallstudie. Detta är ett av de torraste områdena i Medelhavsområdet, där jordbruket är en av de viktigaste ekonomiska resurserna, och där korn är den viktigaste grödan som produceras utanför växthus. Kornets tillväxt modellerades med hjälp av AquaCrop-modellen i dess Python-implementering, AquaCrop-OSPy. Modellen ställdes in för att undvika lokal omkalibrering av kornparametrarna och för att fånga fleråriga trender i produktivitetsförändringar, snarare än den mellanårliga variationen. Studien fokuserade på två 30-årsperioder: mitten av århundradet (2041-2070) och slutet av århundradet (2071-2100), och på scenarierna SSP1-2,6, SSP2-4,5 och SSP5-8,5 för de gemensamma socioekonomiska vägarna. För varje tidsperiod och SSP-scenario utvärderade forskningen också tre underscenarier av markvatteninnehåll vid sådd: med parametern inställd på 10%, 20% respektive 30% av det totala tillgängliga vattnet (det vatten som finns i jorden som är tillgängligt för grödan för att upprätthålla sitt liv). Efter att ha uppskattat effekterna av klimatförändringarna analyserade forskningen olika anpassningsvägar (bevattning, applicering av mulcher och förändring av sådatum) för att utvärdera deras prestanda för anpassning till klimatförändringar i området.

Resultaten visar att markvattenhalten är viktig för att upprätthålla god avkastning eller minska förlusterna, och visar att den möjliga genomsnittliga avkastningsförändringen är mellan +14% och -45% vid mitten av århundradet och mellan +12% och -55% vid slutet av århundradet. Den större variationen i produktivitet är förknippad med markvatteninnehållet vid sådd, snarare än på SSP-scenariot, med SSP5-8.5 som det enda som visar en markant skillnad jämfört med de andra. När det gäller bevattning visar resultaten att med en markvattenhalt vid sådd på 10% av det totala tillgängliga vattnet, kan bevattning upp till 100 m^3 / ha inte vara tillräcklig för att undvika produktivitetsförluster. Studien visar också att en optimal tröskel för att utlösa bevattning i anpassningssyfte kan hittas mellan 0% och 20% av det totala tillgängliga vattnet. Sammantaget visar studien hur anpassning genom bevattning kan vara genomförbar i provinsen. Arbetet tyder dessutom på att mulcher är effektiva som en anpassningsstrategi för att delvis begränsa bevattningsvattenbehovet i framtiden och förbättra grödans avkastning. Forskningen visar dock inte på någon tydlig fördel med att ändra sådatumet till tidigare eller senare sådatum, men antyder vikten av att korrekt utnyttja såfönstret för att nå optimal avkastning i framtiden. Dessutom visar arbetet att den metod som används för att genomföra denna forskning är lämplig för att bedöma trender i avkastningsförändringar på flerårig skala, om det analyserade tidsfönstret är större eller lika med 10 år, och om ett fel på cirka 10% på resultaten accepteras.

Acknowledgments

This thesis was carried out at the *Faculdade de Ciências da Universidade de Lisboa*, hosted by the *Center for Ecology, Evolution, and Environmental Changes (CE3C)*. I want to express my gratitude to my supervisor in Lisbon, Tiago Capela Lourenço, for having warmly welcomed me into his research group, guiding me through my work, giving me the chance to take part in the activities of his team, and teaching me a lot about climate change adaptation. My sincere thanks go to my supervisor at KTH, Luigia Brandimarte, who followed me through my thesis, being always supportive and available for guidance. Also, I want to thank my supervisor at Politecnico di Torino, Elena Comino, to whom I am thankful for the relationship that has developed during my university years.

Lastly, I want to thank all my colleagues in room C1 at CE3C for having welcomed me in their team. Among all, I want to express my gratitude to Ricardo and Roy, who helped me to develop my thesis, spending time with me to discuss the issues that I encountered throughout the work, and providing me with crucial and continuous advice, feedback, and material to improve my work.

Forenote

This thesis was carried out within the framework of the European project *RethinkAction,* funded under the Horizon 2020-EU.3.5 research and innovation programme under grant agreement No. 101037104.

The project focuses on land use based climate change adaptation and mitigation solutions, and aims at creating a cross-sectoral decision-making platform for different end users. It focuses on six case studies covering the main European climates and environments, the Almeria province being the Mediterranean case study.

The proposed research used the tools indicated in the *RethinkAction* project, along with the climate data provided by the partners of the project.

The results of this thesis were presented to local stakeholders in Almeria on the 25th of January 2024 during a workshop organized within the *RethinkAction* project.

Table of Contents

List of Figures

Appendix

List of Tables

Appendix

List of Abbreviations

FAO – *Food and Agriculture Organization*

ISWC – *Initial Soil Water Content*

RCP – *Representative Concentration Pathways*

SSP – *Shared Socioeconomic Pathways*

TAW – *Total Available Water*

USDA – *United States Department of Agriculture*

1. Introduction

The Mediterranean is often pointed at as a climate change hotspot (Lionello & Scarascia, 2018), with more intense warming and drying projected in the region than in other areas of the world (Cos et al., 2022). Such changes in climate will impact the countries and the communities of the Mediterranean in various ways, magnitudes, and sectors (Ali et al., 2022). Among these, it is widely accepted that agriculture will be one of the most affected sectors. With projected decreased yields, greater irrigation needs (Ali et al., 2022; Masia et al., 2021), and reduced water availability (Giuntoli et al., 2015; Roudier et al., 2016).

Among the crops that will suffer the effects of climate change is barley, one of the most grown cereals throughout the Mediterranean, particularly in arid and semi-arid areas (Cammarano et al., 2019) due to its resilience and adaptability to stress conditions (Cossani et al., 2007; Slafer & Savin, 2023; Steduto et al., 2012). These characteristics, often make barley a “last option” in particularly harsh areas, or under extraordinarily stressful conditions (Slafer & Savin, 2023). Studying how climate change will impact this crop is therefore relevant since it means looking at one of the most resilient crops available to farmers, a “safety net” on which to relay in case of harsh conditions.

Notwithstanding its resilience to adverse climatic conditions, the average productivity of this crop is projected to decrease in the future due to climate change. This trend, however, has a wide local variability (Cammarano et al., 2019). To provide stakeholders with more detailed information to drive climate change adaptation it is therefore important to understand how different areas will be impacted. (Ali et al., 2022).

To evaluate the impacts of climate change on crop yield, crop models are often used. Among these AquaCrop is the model developed by the Food and Agriculture Organization (FAO) with the aim of being particularly suitable for conditions in which water is the main limiting factor for crop’s growth (Steduto et al., 2012). Making it ideal for crop modeling in the Mediterranean. Being created for field-scale crop modeling, the inputs provided to AquaCrop ideally need to have high quality (Steduto et al., 2012). Among all, adapting to local varieties and conditions the parameters that describe each crop can greatly improve the model’s precision. This step is however extremely time and resource-consuming, requiring multi-year field experiments and vast local agronomic knowledge (Daničić et al., 2019; López-Urrea et al., 2020). However, as per the literature (Steduto et al., 2012), the effort for inputs’ quality can be limited when the scale is widened to areas larger than the single field, and if the aim is to capture trends at larger time scales. In this perspective, the most important simplification in the use of AquaCrop is to not carry out any local recalibration, only using the standard datasets available within the model. Such an approach, while significantly renouncing accuracy in inter-annual projections, might still provide insights on yield change trends, also allowing a more straightforward use of the model.

The Mediterranean offers many interesting case studies. Among these, the province of Almeria is peculiar due to its arid climate but strong reliance on agriculture, mainly based on greenhouses, which makes it one of the most important producers of fruit and vegetables in Europe (Aznar-Sánchez et al., 2020). In this context, barley is the principal crop grown outside of greenhouses. Additionally, it is mainly grown under rainfed conditions (Ministero de Agricultura Pesca Y Alimentacion, n.d.), and in areas far from the ones where intensive agriculture is practiced (d'Andrimont et al., 2021). This makes barley an alternative to the dominant model of agricultural production (greenhouses), which comes with important social and economic issues (Castro et al., 2019; Gertel & Sippel, 2014). While also being among the livelihood sources of areas far from the coast, where greenhouse horticulture is practiced.

1.1 Aim of the study

This study aimed at analyzing the climate change impact on rainfed barley in the province of Almeria by evaluating the yield change under two 30-year time periods: mid-century (2041-2070), and end-century (2071-2100) by comparing them with a baseline period (1985-2014). For each time period, three different SSP scenarios were analyzed: SSP1-2.6, SSP2-4.5, and SSP5-8.5. Within each time period, and SSP scenario, three sub-scenarios of soil water content at sowing were addressed: with the parameter set at 10%, 20%, and 30% of the Total Available Water. The research used the FAO's AquaCrop model in its Python implementation, AquaCrop-OSPy. The standard barley dataset available in AquaCrop was used, without any re-calibration for local conditions.

This work targeted five research questions, addressing AquaCrop-OSPy modelling potential, climate change impact, and climate change adaptation:

1. How well-suited is the standard AquaCrop barley crop parametrization to model multi-year trends in rainfed barley production in the Almeria province?
2. What are the projected trends of rainfed barley yield change at mid-century (2041-2070), and end-century (2071-2100), under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios?
3. When using irrigation as an adaptation strategy, what will be the irrigation demand for barley in the analyzed scenarios and how will this affect yields?
4. How will the application of mulches affect irrigation needs and yields?
5. How will changing the sowing date impact rainfed barley yields?

2. Background and case study

2.1 Literature review

As mentioned by Steduto, et al. (2012), one of the application fields of the FAO’s AquaCrop model is evaluating the impact of climate change on crop productivity and water use. Through time, different studies applied this tool focusing on barley. Daničić, et al. (2019) used the FAO model in the case study of northern Serbia to evaluate how the crop’s yield and the water use were impacted by the changing climate, the economic feasibility of irrigation, as well as changes in the phenology of the plant. Using 8 years of field experiments to calibrate and validate the model, and a single future climate scenario, the researchers showed how changes happened in the phenology of the crop, such as earlier sowing date and shortened flowering time, but the yields were not largely impacted. Daničić, et al. (2019) considered various parameters, Dubey and Sharma (2018), used instead climate as the only variable to evaluate changes in the yields of maize, barley, and wheat in the Banas River basin, India, from 2021 to 2050. They showed how in that case study yields are projected to increase, particularly under Representative Concentration Pathway (RCP) 4.5. Similarly, Yawson, et al. (2016) simulated the impact of climate change on spring barley in the UK, using literature sources to calibrate the crop, and covering all 14 administrative regions of the country. The same author used the model to focus on food security (Yawson, et al., 2020a), and on malting barley (Yawson, et al., 2020b). Arce-Romero, et al. (2018), analyzed instead two Mexican case studies, and projected yield decreases in the future, with milder impacts when implementing adaptation measures such as changing planting dates and applying mulches to reduce evapotranspiration.

Insights on how AquaCrop has been used to assess climate change impacts can also be found in studies focusing on other crops. Bird, et al. (2016) studied the impact of climate change on irrigated tomato and rainfed wheat for two watersheds respectively in Tunisia and Sardinia. They apply an interesting approach, evaluating the economic impacts of climate change and evaluating the effects of adaptation strategies while minimizing the effort for calibration (Bird et al., 2016). For Mediterranean case studies, besides wheat (Soddu et al., 2013; Saadi et al., 2015), AquaCrop has also been used to model future trends in cotton yields (Voloudakis et al., 2015), sunflower (Voloudakis et al., 2015), and tomato (Katerji et al., 2013).

To have a better understanding of how barley has been handled with AquaCrop, it is interesting to have an overview of cases of application of the model on barley that do not only aim at climate change impact analysis. Tavakoli, et al. (2015) used this tool to evaluate the effects of a deficit irrigation strategy for growing barley in Iran. Marinez-Romero, et al. (2021), paired it with MOPECO models to optimize irrigation under water deficit conditions in the Spanish region of Castilla-La Mancha. A co-author of this study also published a parametrization of high-yielding barley in the same region under various irrigation scenarios (López-Urrea et al., 2020). Lastly, El Mokh (2014) used AquaCrop to develop strategies for barley cropping in saline conditions in Tunisia.

Crop calibration approaches for AquaCrop

It is relevant to notice how all the mentioned studies include to different extents a crop's calibration, to better adapt it to local conditions. Such calibration happens mainly through field experiments (Daničić et al., 2019; Dubey & Sharma, 2018; López-Urrea et al., 2020; Tavakoli et al., 2015), or through literature (Arce-Romero Antonio and Monterroso-Rivas, 2018; Yawson et al., 2016). Especially for experimental calibration, such a process requires multiple years of data and agronomic knowledge, making the process resource and time demanding.

Calibration of crop parameters is then validated through experiments that last a few years using statistical indicators such as Root Mean Squared Error, Index of Agreement, Nash-Suitcliffe efficiency, and Goodness of Fit (Daničić et al., 2019; López-Urrea et al., 2020; Saldaña-Villota & Cotes-Torres, 2021; Tavakoli et al., 2015). Alternatives for calibration exist, such as using satellite imagery (Han et al., 2020; Kim & Kaluarachchi, 2015), algorithms (Guo et al., 2021), or both in combination (Zhang et al., 2019). Through a sensitivity analysis, it might also be discovered that some parameters are more important than others to calibrate (Jin et al., 2018). Also, as done by Bird, et al. (2016), calibration can be carried out by focusing only on a few parameters and fine-tuning them to find the best fit.

This process of calibration, however, does not always guarantee excellent results. Coudron et al. (2023), highlight how uncertainties in the model coupled with uncertainties related to increased differences in local climates due to climate change will anyways compromise the results to a certain extent, especially for larger scale applications.

When it comes to crop parameters, FAO explicitly mentions that "*AquaCrop is designed to be widely applicable under different climate and soil conditions, without the need for local calibration, once it has been properly parameterized for a particular crop species.*" (Steduto et al., 2012). The same source also indicates the minimum parameters to be locally calibrated to get first-order approximations from AquaCrop: Harvest Index, duration of life cycle, and seedling/germination (Steduto et al., 2012).

It is also useful to remember that AquaCrop is a tool designed to model yields at the field scale (*AquaCrop Training Handbooks*, n.d.), requiring high quality inputs to develop optimal management strategies and forecasts. This loses importance when expanding the scale, as done by Roos, et al. (2021) who developed a regional implementation of AquaCrop using a generic C3 crop for the whole Europe (de Roos et al., 2021).

Large-scale applications of crop models and their limitations

Several examples of large-scale applications of AquaCrop exist (de Roos et al., 2021; Yawson et al., 2016), and even more of crop models in general (Chipanshi et al., 1999; Jagtap & Jones, 2002; Reidsma et al., 2009; Supit, 1997). As mentioned by Therond, et al., (2011), these approaches introduce different approximations because of the difficulties in retrieving data that well represent the spatial variability of the corresponding inputs (climate, soil type, field management practices, etc.). Reidsma, et al. (2009) talk about the frequency with which the results of a crop model on larger scales do not agree with the observed data. They investigate the role of varying field management practices, environmental, and socio-economic variability on such differences. When addressing this issue, Therond, et al.(2011), propose a method to calibrate crops on a regional scale with a low amount of data and by roughly adjusting crucial parameters to local conditions, showing that by doing so it is possible to capture the major variability within Europe. They compare the performances obtained with a pre-parametrized, not locally calibrated crop, and those obtained with their method, showing that while a minimal calibration improves the model performances, for two crops (soft wheat and durum wheat) out of three such impact was not substantial (Therond et al., 2011).

Projected climate change impact on barley in Spain and the Mediterranean

No studies that applied the AquaCrop model to assess climate change impacts on barley production in the Mediterranean have been found. However, a few papers that address this topic with other crop models and approaches exist. Here a summary of their findings is reported.

Cammarano, et al. (2019), addressed the issue by differentiating between three scenarios: “dry”, “mid”, and “wet”, and reported how, at mid-century under RCP 4.5, the yields decreased by 27% in the dry scenario, but increased respectively by 4% and 8% in the mid and wet scenarios. Within his results, the author stresses the importance of soil water content at the beginning of the growing season and of heat stress as critical factors to negatively impact barley yields in the future (Cammarano et al., 2019). A second study, focusing on a semi-arid basin in Jordan (Al-Bakri et al., 2011) analyzes different scenarios at mid-century and indicates how barley yields are negatively impacted in the future under all scenarios of rainfall change and temperature change. Also stressing the importance of soil water conservation strategies.

Concerning the south of the Iberian peninsula, Bento, et al., (2021) for a mid-century timeline (2042-2070) and for RCP 4.5, and RCP 8.5, project significant yield losses in barley. Hypothesizing that in the future this cereal might not be a suitable source of livelihood for local farmers anymore.

Lastly, Al-Bakri et al. (2021) showed how in different locations throughout the Middle East and northern Africa barley yields are projected to decrease under the emission scenarios RCP4.5 and RCP8.5, at both mid-century (2030-2050) and end-century (2080-2100), at a rate between 5% and 30%. The researchers suggest that when this does not happen, rainfall is the crucial player, staying almost constant while temperatures increase.

2.2 Case study

Geography and climate

The Almeria province is located in the south-east of Spain (Figure 1), and is part of the *Comunidad Autónoma de Andalucía,* it borders the provinces of Granada (west) and Murcia (north-east), and the Mediterranean sea (south, south-east). The overall area is 8.774 Km^2 (Diputacion Provincial de Almeria, 2009).

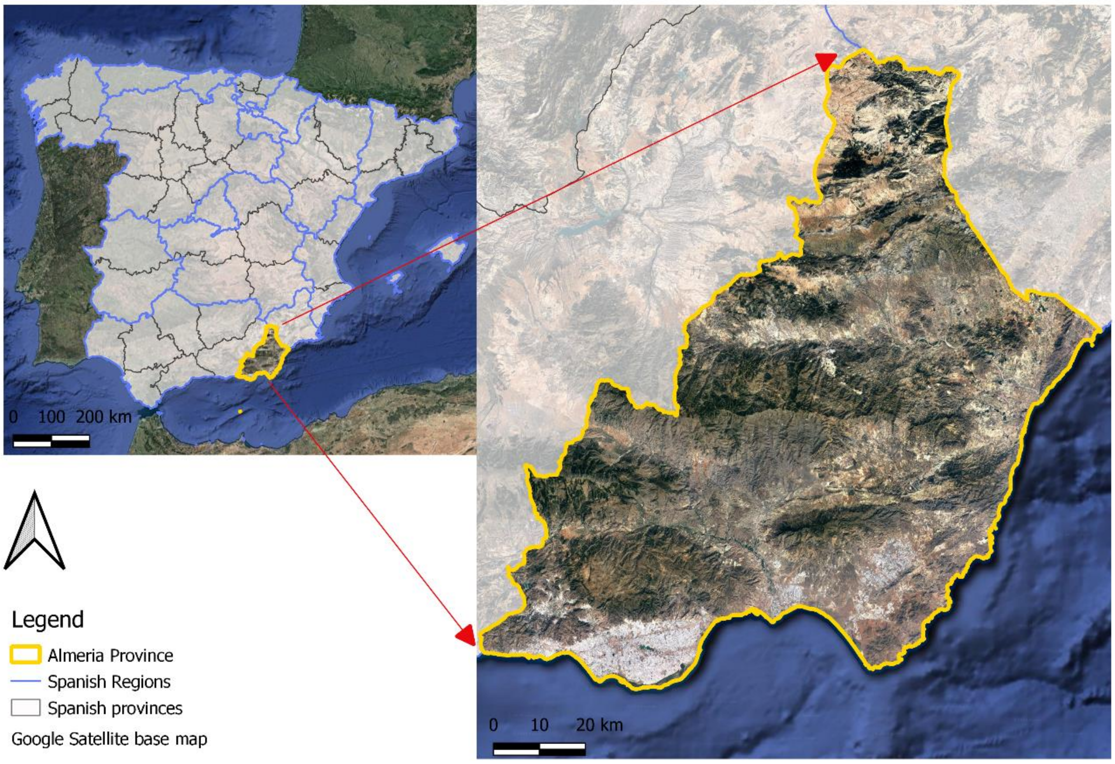

Figure 1. *Almeria province's location in Spain and its physical map.*

The area is extremely arid, especially in the south and in the east, with an average yearly precipitation of 300 mm, and a high mean temperature of 18 °C (Diputacion Provincial de Almeria, 2009). These values vary significantly due to the physical characteristics of the province which has important elevations, with almost 40% of the territory within 700 and 1400 meters on sea level. (Diputacion Provincial de Almeria, 2009). Yearly, precipitations vary from 175-300 mm in the lower-land area, up to more than 550 mm in the Sierra Nevada (Instituto de Estudios Almerienses, 2009). The west and the north parts are the rainiest areas, while the south and the east are drier, with less than 30 yearly rainy days in numerous meteorological stations (Pulido Bosch, n.d.). A similar trend is also followed by temperatures. The interaction between rainfall and temperature causes important issues related to water availability with a water deficit that can last up to 12 months in specific areas of the South (*Cabo de Gata*) (Diputacion Provincial de Almeria, 2009).

Thanks to the data available from the *JRC MARS Meteorological Database* (Toreti, 2014), with data from 1980 to 2019 from meteorological stations interpolated on a 25km-by-25km grid, it is possible to outline the main climatic trends within the province. Figure 2 shows the evolution in yearly average maximum and minimum temperatures from 1980 to 2019, clearly outlining an increasing trend in both values.

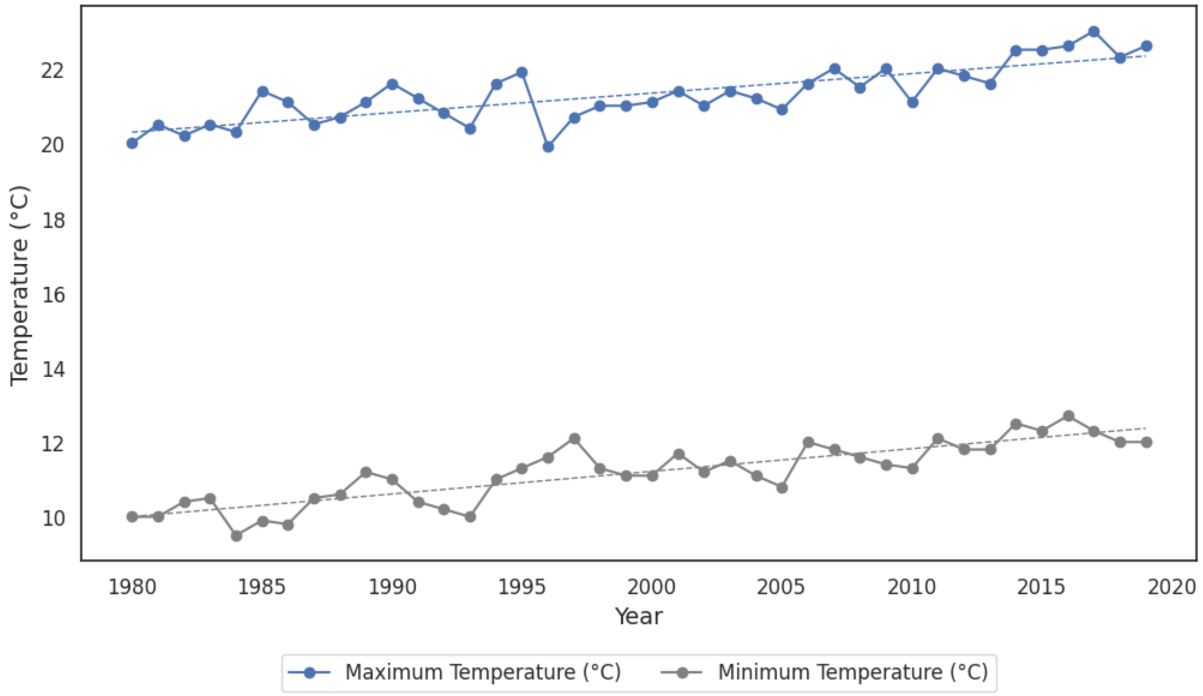

Figure 2. *Almeria's average yearly maximum and minimum temperatures for the years 1980-2019 (Toreti, 2014).*

Figure 3 reports instead how average monthly cumulative precipitation and monthly cumulative evapotranspiration evolved in the same period. Showing a trend with increasing precipitations and decreasing potential evapotranspiration.

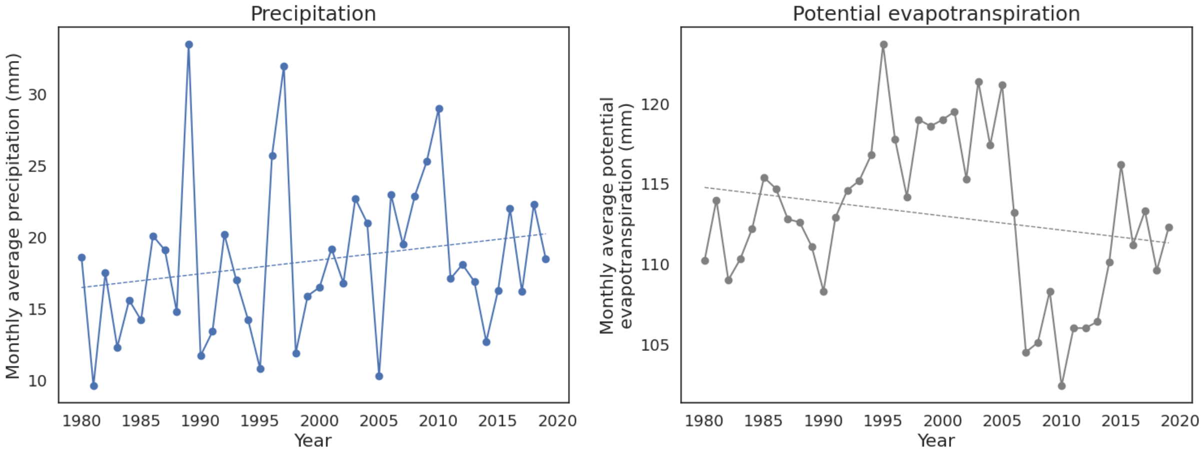

Figure 3. *Average monthly cumulative precipitation (left) and potential evapotranspiration (right) in Almeria for the years 1980-2019 (Toreti, 2014).*

The same dataset used before allows to outline the monthly distribution of rainfall, potential evapotranspiration, maximum and minimum temperature, as shown in Figure 4. From this Figure, it is clear how the wettest month is November, and how overall Autumn is the season in which the bulk of the yearly precipitation accumulates. Lastly, potential evapotranspiration, along with minimum and maximum temperatures, reaches its maximum in summer, between August (temperatures), and July (potential evapotranspiration).

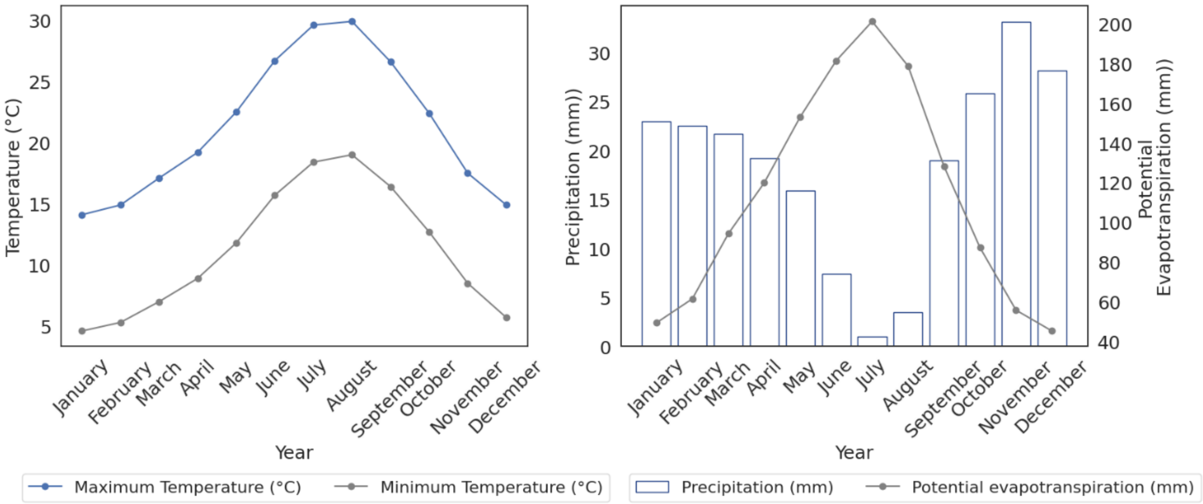

Figure 4. *Monthly distribution of maximum and minimum temperature (left), precipitation and potential evapotranspiration (right) in Almeria from 1980 to 2019 (Toreti, 2014).*

Barley production in Almeria

Barley is the most important open-air grown crop in the Almeria province (Instituto de Estatistica y Cartografia de Andalucia, 2018). This crop is classified by the Ministry of Agriculture as a winter crop, and the main variety grown in Almeria is the six rows barley (Ministero de Agricultura Pesca y Alimentacion, 2019). As shown in Figure 5, it is almost exclusively grown in the northern part of the province, where temperatures are milder and precipitation more abundant.

Regarding the commercial use of barley, while no data specific for the Almeria province have been found, in Spain the bulk of barley produced (88%) is sold outside the farm, and what is kept inside is used mainly as animal feed (9%) (Ministero de Agricultura Pesca y Alimentacion, 2019). National data moreover report that the two main outputs of Barley production are grain and hay (Ministero de Agricultura Pesca y Alimentacion, 2019).

Most of the barley fields in Almeria are rainfed (8149 hectares versus 290 hectares irrigated in 2018) (Ministero de Agricultura Pesca y Alimentacion, 2019). The crop is sown between October and December and harvested at the end of the spring (Subsecretaría de Agricultura & Pesca y Alimentación, 2014). The sowing date is thus variable, and, according to what mentioned by Russel (1990), in arid areas sowing takes place based on a minimum amount of rainfall fallen since the beginning of the wet season.

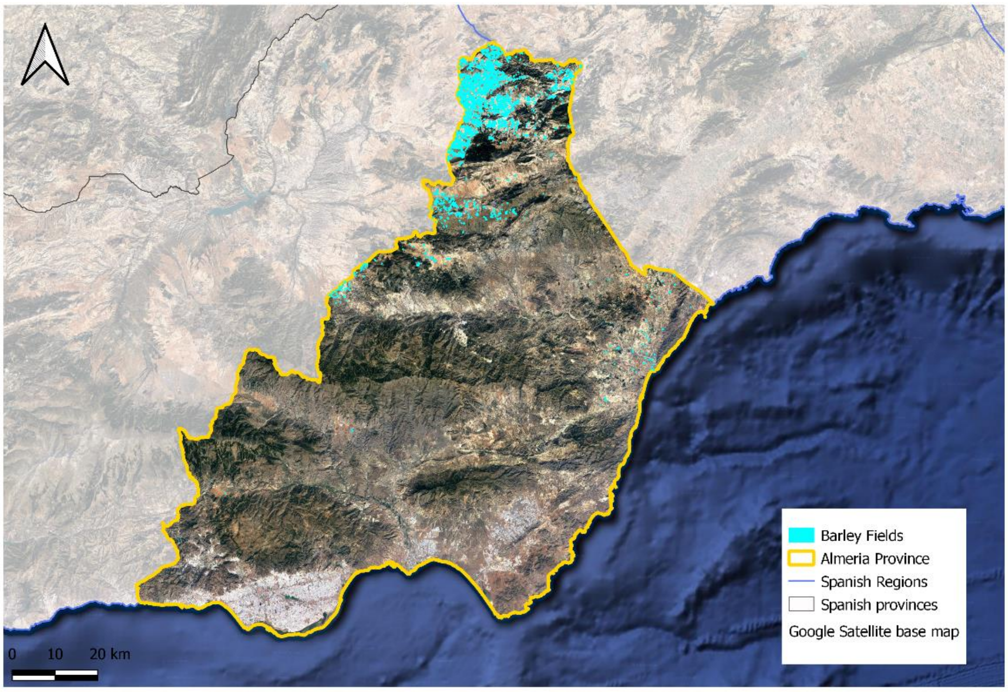

Figure 5. *Map of barley fields in the Almeria province, from the EUCROPMAP 2018 (d'Andrimont et al., 2021).*

Figure 6 shows the evolution in time of barley production in the province of Almeria and the respective total sown area (Ministero de Agricultura Pesca Y Alimentacion, n.d.). It is clear how since the beginning of the 21st Century both the production of grain and the area sown have decreased compared to the last two decades of the 20th century. Such a pattern might be linked to the growth of greenhouse-based agriculture in the province, thus mirroring a shift in agricultural practices.

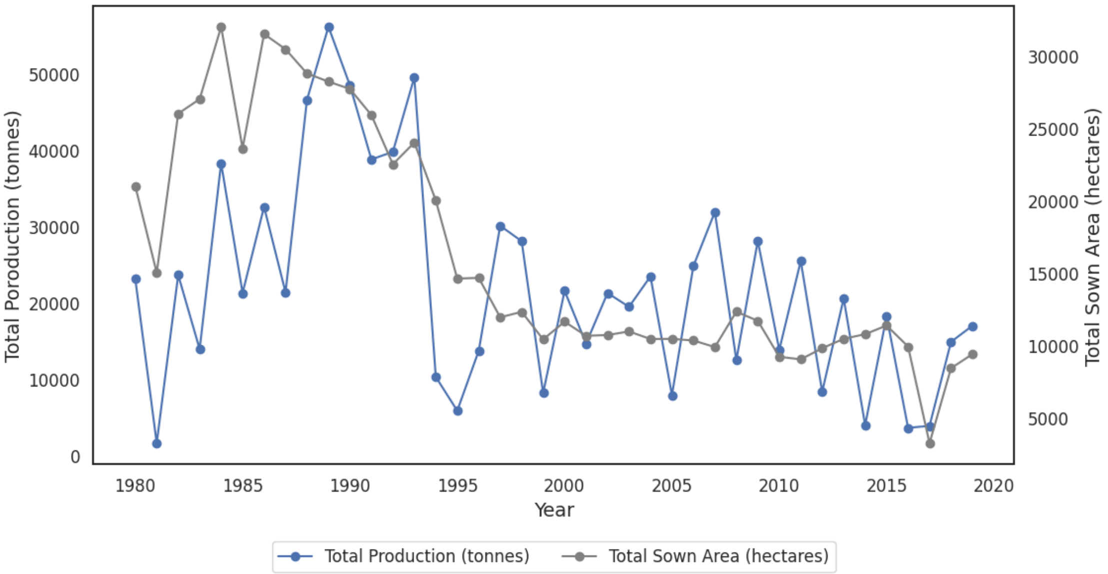

Figure 6. *Comparison between total grain production from barley, and total sown area from 1980 to 2019 in the Almeria province (Ministero de Agricultura Pesca Y Alimentacion, n.d.).*

Figure 7 reveals the trends in barley productivity through the years 1980-2019. It is interesting to notice how the productivity of rainfed barley matches for almost all the years the productivity calculated as the ratio between the total grain production and the total sown area. This indicates that the irrigated areas are much less than the rainfed areas, as they have almost no impact on the productivity calculated as total production over the total sown area. Where it is practiced, irrigation enhances productivity of around 1.5 tonnes/hectare.

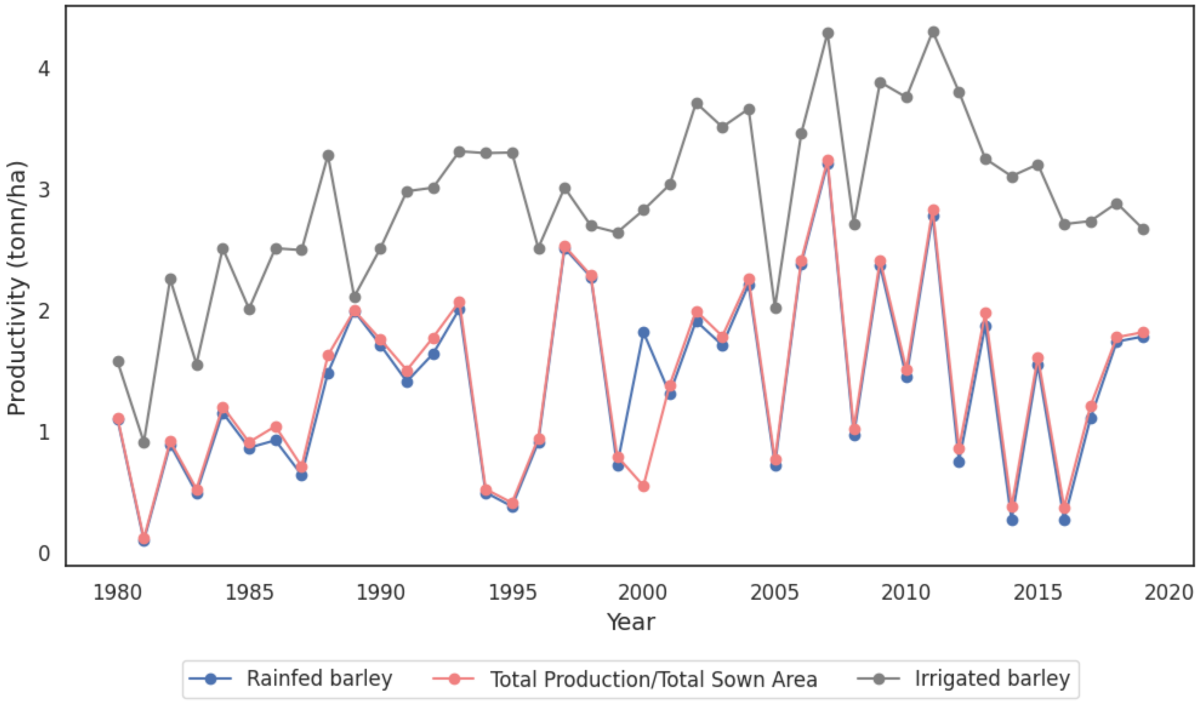

Figure 7. *Comparison between total grain production from barley, and total sown area from 1980 to 2019 in the Almeria province (Ministero de Agricultura Pesca Y Alimentacion, n.d.).*

Climate change scenarios for the Almeria province

Understanding how the Almeria province's climate will change is crucial to analyzing the future trends in barley production in the area. To do so, the climate change projections data provided by the *RethinkAction Project* team (Reder et al., 2023), can give indications on the main trends in maximum and minimum temperature, rainfall, and potential evapotranspiration from 2040 onwards and for the three SSP scenarios of interest for this work. The evolution of each variable is expressed in terms of percentual change from the modeled ensemble average of the period from 1985 to 2014 for a matter of coherence. Figure 8 shows the trends for the different climatic variables in the three different climatic scenarios analyzed.

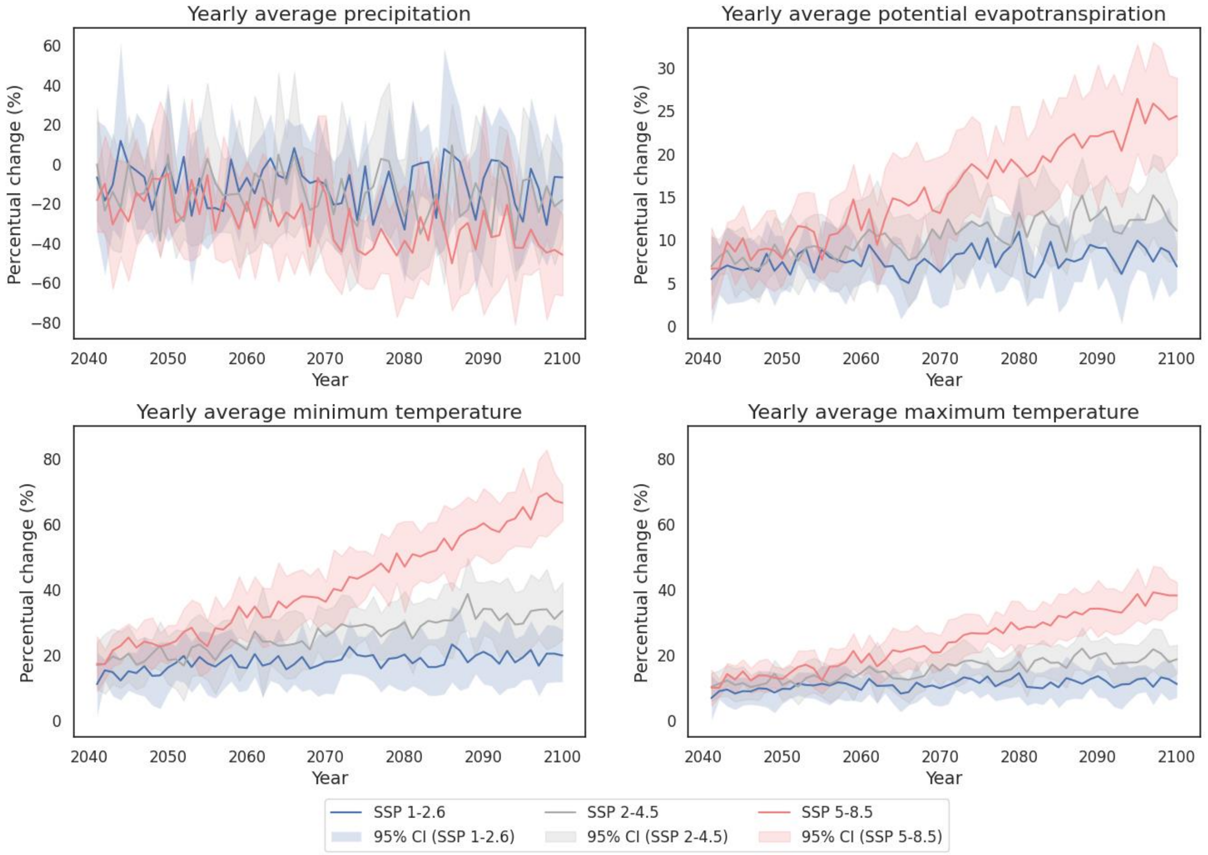

***Figure 8**. Projected percentual changes in precipitation (top right), potential evapotranspiration (top left), minimum temperature (bottom right), and maximum temperature (bottom left), under SSP1-2.6, SSP2-4.5 and SSP5-8.5, compared to the modelled mean of the baseline period (Reder et al., 2023).*

From these graphs, it is clear how scenario SSP 5-8.5 is projected to have the greatest impact on the province's climate, leading to higher maximum and minimum temperatures, and potential evapotranspiration, particularly at the end of the century (after 2070). On the other hand, the other two scenarios stay close to each other, and the 95% intervals overlap throughout all the analyzed periods. It is also interesting to notice how minimum temperature is the variable that shows the largest increases, reaching up to +80% under SSP5-8.5 in 2100. Maximum temperature instead, only increases up to +40% under the same scenario and same timeline.

Precipitation trends are the only ones that do not show a clear difference between the scenarios, and, while indicating that a decrease in mean monthly precipitation is likely, show high variability in the results, with years in which precipitations might exceed the mean of the baseline period, even in SSP5-8.5. These results, as the ones for the other climatic variables, are in line with what is described by the Junta de Andalucia (2022) for the region. The same source provides information on the spatial variability of climate change in the area, indicating how under scenarios SSP2-4.5 and SSP1-2.6 in winter and in autumn the northern and eastern parts of the province could receive more precipitation than in the past. This is interesting for local agricultural production, particularly concerning the barley cropping areas reported in Figure 5.

While the trend in precipitation change is not extremely clear, the one in potential evapotranspiration change clearly shows an increase. Then, the difference between precipitation and potential evapotranspiration is projected to decrease in the future under each scenario, indicating possible increasing water stress in the province (Junta de Andalucia, 2022). This variation can be acknowledged through Figure 9, where it is clear how the difference between precipitation and potential evapotranspiration stress will move from values close to -20%, up to around -60% in SSP5-8.5. Here again, not much difference exists between SSP1-2.6 and SSP2-4.5, while SSP5-8.5 largely diverges from them at the end of the century. These trends give hints in terms of reduced soil water availability in the future, a parameter whose importance is remarked by different studies, as in Cammarano (2019) and (Al-Bakri et al., 2011).

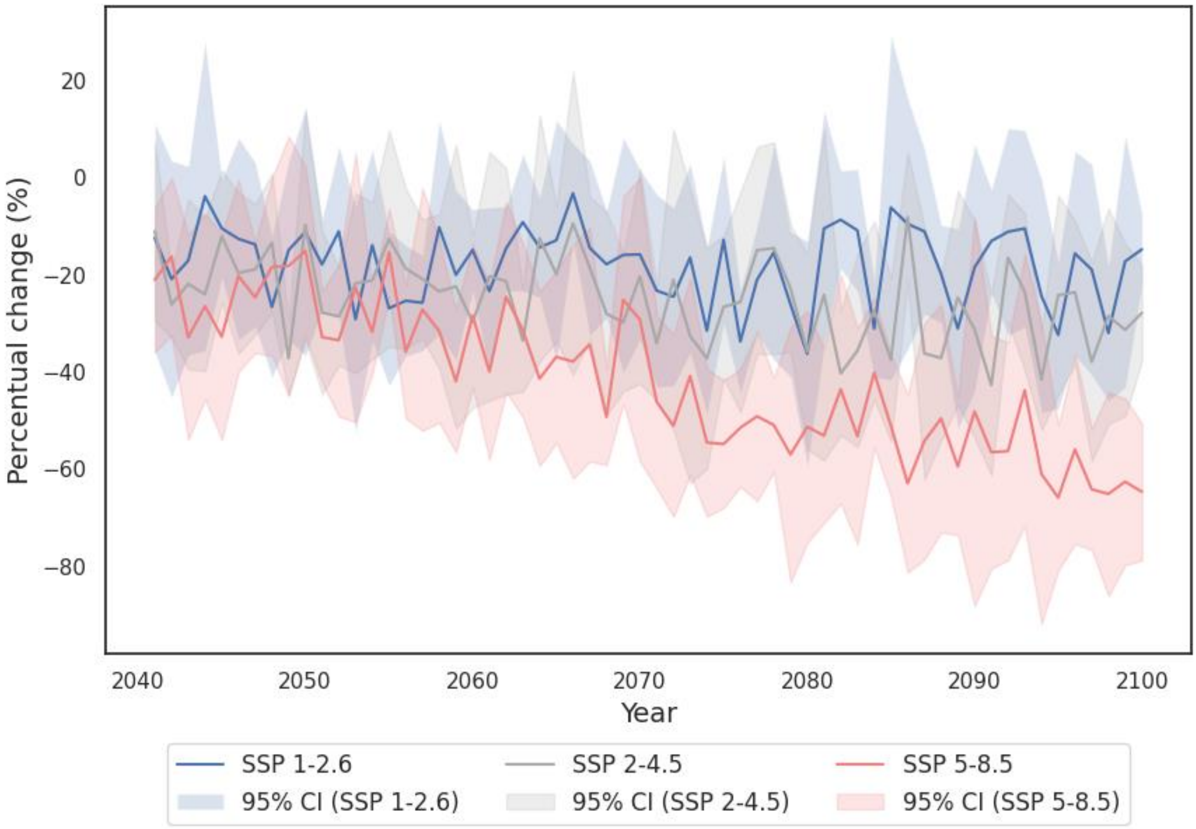

Figure 9. *Yearly average percentual change in mean monthly difference between precipitation and potential evapotranspiration from 2040 to 2100, compared to the baseline period (1985-2014).*

Adaptation policies for the agricultural sector

On a national level, Spain has produced a *National Climate Change Adaptation Plan* for the years 2021-2030 (Ministerio para la Transición Ecológica y el Reto Demográfico de España, 2020), which outlined the main adaptation actions to be developed in the nation. With regards to the agricultural sector, the main *Lines of Action* that can apply to barley*,* are:

- **Line of Action 6.4:** Foster practices that promote the resilience of the food system to climate change, such as organic farming, precision agriculture, and conservation agriculture.

- **Line of Action 6.5:** Communication actions to inform about the relationship between food and climate change. This includes information about production systems, distribution, food waste, and environmental costs of food production.

To promote climate change adaptation, the region Andalucia has developed the *Plan Andaluz De Accion Por El Clima* (Junta de Andalucía. Consejería de Agricultura Ganadería Pesca y Desarrollo Sostenible., 2021) where guidelines for climate change adaptation and mitigation for the region are outlined. For the agricultural sector, two strategic pathways (SP) are defined, which include different measures. The table below shows the most significant ones for barley cropping.

Table 1. *Strategic pathways and linked measures for adaptation of the agricultural sector to climate changes in Andalucia (Junta de Andalucía. Consejería de Agricultura Ganadería Pesca y Desarrollo Sostenible., 2021).*

Strategic Pathway	Measure
AC1: Increasing knowledge around impacts, risks, and adaptation solutions within the agricultural sector (i.e. for the main crops), including in its relationship with the food sector.	• **AC1.M2:** Farm advisory services • **AC1.M4/AC1.M5/AC1.M6:** Support in the creation and operation of task forces for productivity and environmental sustainability in the agricultural sector
AC2: Promoting agricultural practices that improve adaptation to climate change and resilience, within the framework of the common agricultural policy.	• **AC2.M10:** Aid for farms and infrastructures aimed at reducing adverse impacts of climate change and natural disasters on the production potentials of farms (i.e. irrigation infrastructures)

While these guidelines express the will of the national and local governments to progress in the adaptation to climate change, they fail to indicate practical solutions to do so. Such indications can instead be found in other sources, more specialized in the sector. In 2018, the Union de Pequenos Agricultores y Ganaderos (UPA) (2018) issued the *Manual de adaptacion frente al cambio climatico. Ganaderia.* The document reports a few solutions to practically adapt the agriculture of herbaceous crops. Among these, the main ones that can apply to barley are outlined in the table below.

***Table 2**. Adaptation measures for barley from Unión de Pequeños Agricultores y Ganaderos (UPA) (2018).*

Adaptation Measure	Description
Change in planting date	To adapt crops to the new climatic conditions and capture the best window for crop development
Combine earlier sowings with varieties with longer cycles	For higher temperatures that will shorten the plant's life cycle, combined with irrigation in the flowering stage and early sowing in autumn when rain is available.
Use short-cycle varieties	For areas with no rain in autumn so that sowing cannot happen, in these areas it is suggested to plant short-cycle varieties before spring, to avoid a low crop emergence rate
Maintain a cover of organic matter on the soil	This technique preserves the water in the soil, increases biodiversity, and reduces the need for labor on the soil.
Organic Fertilization	Fertilization reduces mineral nitrogen application, which prevents soil erosion, and maximizes the efficient use of water.

From these guidelines for adaptation emerges the will to inform farmers about the different available options, and co-developing strategies to improve resilience towards climate change. Concerning the practical solutions to be implemented reported in Table 2. These are related to two main areas of action: seizing the ideal conditions for the crop's growth and acting on the soil to improve its characteristics. Within these two areas, changing the sowing date of the crop, and applying an organic cover on the soil seem to be the ones that are more readily applicable by farmers, implying the least intervention on the overall cropping system and the environment.

3. Data and methods

3.1 The AquaCrop model

In this work, crop growth has been simulated using the AquaCrop model, in its Python implementation (AquaCrop-OSPy): a dynamic crop model developed by FAO to simulate the yield of herbaceous crops as a function of water consumption (Steduto et al., 2012). Because of this characteristic, the model poses particular importance on conditions of water stress for the plant and estimates crop yield directly from the actual crop transpiration, the *productive evapotranspiration*, through the core equation:

$$(1)\ B = WP \cdot \Sigma Tr$$

Which represents the linkage between the produced biomass (B), expressed in kg per m^2, and the crop transpiration (Tr), expressed in mm or m^3, through the Water Productivity parameter (WP), expressed in kg per m^2 and mm, or in kg per m^3 of water transpired (Steduto et al., 2012).

This core equation alone, however, does not result in the final yield; indeed, this is just a part of the total produced biomass. AquaCrop links the two values through a third parameter, the Harvest Index (HI), as

$$(2)\ Y = HI \cdot B$$

Where Y is the final yield.

The model has 4 main components: climate, crop, soil, and management, which are considered within the model's equations and impact the results (Steduto et al., 2012). Stresses, then affect the equations and the parameters linked to these four components through coefficients that range from 0 to 1, and that are described by a specific curve (Steduto et al., 2012). Water and temperature stresses are the most important ones within AquaCrop; however, other ones exist, namely aeration stress, low soil fertility stress, and soil salinity stress.

AquaCrop-OSPy

For this work, the choice has been to use AquaCrop-OSPy, the Python implementation of AquaCrop, developed by Thomas Kelly and Timothy Foster in 2021 (Kelly & Foster, 2021a), in the latest version available at the start of the work, the 2.2.3, released in December 2022. AquaCrop-OSPy preserves the same core equations as the version of AquaCrop directly developed by FAO and allows the retrieval of the same outputs (Kelly & Foster, 2021). However, being implemented in Python, it allows for much easier data analysis and data manipulation, along with the possibility of modifying the code to produce more personalized results.

The main difference that was found with the AquaCrop version directly developed by FAO, is that AquaCrop-OSPy does not allow to explicitly link the simulations of one year with the successive when simulating multiple years (i.e, 30 years), not allowing to have a continuous soil water balance throughout all the simulation years. In AquaCrop, the initial soil water content for the growing season of year *i+1* is the result of the soil water content at the end of the growing season of the year *i,* plus the water balance in the off-season until the sowing date of season *i+1*. However, AquaCrop-OSPy resets the initial soil water content to the default value provided as an input for every single growing season. This was a crucial issue to be faced, and the way of overcoming it is explained as follows.

Inputs required by AquaCrop-OSPy

One of the benefits of using AquaCrop-OSPy is that it requires relatively few input data, divided between climatic data, crop and soil characteristics, and management practices (Steduto et al., 2012). AquaCrop-OSPy moreover allows for a high level of customization in the inputs, which lead to different levels of accuracy in the results (Steduto et al., 2012). Table 3 summarizes the minimum inputs required for each input category.

***Table 3**. Minimum input requirements for AquaCrop-OSPy.*

Climate data	Soil data	Crop characteristics	Management practices
Minimum temperature Maximum temperature Potential evapotranspiration Rainfall CO_2 concentrations	Soil texture Soil depth Groundwater table Initial soil water content	Crop type and parameters Calendar type Sowing date	Soil fertility level Weed infestations Practices that affect soil-water balance Irrigation strategy

3.2 Data sources and retrieval of AquaCrop-OSPy inputs

Climate data

Daily climatic variables for the Almeria province were provided by the partners of the *Rethink Action* project (Reder et al., 2023). These were obtained through an Empirical Quantile Mapping Statistical Downscaling approach to downscale Global Climate Models within the framework of CMIP6 (Eyring et al., 2016) on a target grid with 5.5km x 5.5km resolution, using the CERRA climate reanalysis (Schimanke et al., 2022) as training model (Reder et al., 2023). The data from seven CMIP6 models were used: ACCESS-CM2, CESM2, CNRM-ESM2-1, EC-Earth3-Veg-LR, HadGEM3-GC32-LL, IPSL-CM6A-LR, MIROC4, Nor-ESM2-MM. Not all of these models included all the variables needed for the project, and the missing ones were calculated by the partners of the project from the available ones (Reder et al., 2023).

The climatic variables are provided for three different timelines: 1985-2014 (baseline period), 2041-2070 (mid-century), and 2071-2100 (end-century), and three different scenarios: SSP1-

2.6, SSP2-4.5, and SSP5-8.5. These are *Shared Socio-Economic Pathways* (Riahi et al., 2016): scenarios for global developments that comprehend different challenges for climate change adaptation and mitigation (Riahi et al., 2016). These consist of the SSP scenario on which they are based (SSP1 to SSP5), combined with a Representative Concentration Pathways (RCP) scenario, describing trajectories in greenhouse gas concentration in the atmosphere, and therefore the level of radiative forcing reached in 2100 (2.6 to 8.5 $\frac{W}{m^2}$) (Reder et al., 2023). The three analyzed SSP scenarios can briefly be described as follows, according to Reder, et al. (2023)

SSP1-2.6: A sustainable pathway, with limited greenhouse gas emissions.

SSP2-4.5: A middle-of-the-road scenario, where no significant shift from historical trends happens.

SSP5-8.5: The scenario where emissions grow the most, tripling in 2075, as a push for unsustainable social and economic development.

CO_2 concentration

The standard CO_2 concentration datasets available in AquaCrop-OSPy have been used for both the baseline period and for future projections. These data are specific to the analyzed SSPs.

Soil data

Being the spatial scope of the research a province, an approximation is needed, selecting a single soil type for all the barley fields of the region. The process of doing so, along with the data sources used, is described as follows.

Soil texture

Topsoil texture data were retrieved from the European dataset *Topsoil physical properties of Europe (based on LUCAS topsoil data)* (Ballabio et al., 2015), a raster dataset with a resolution of 500 meters that provides information on the USDA (United States Department of Agriculture) soil textural class. This dataset was coupled with the *European Soil Database of 2001* (Panagos, 2006) to check that in the bulk of Almeria's rainfed fields the soil does not have textural changes before 120 cm of depth. Allowing therefore to consider the topsoil data a good approximation of the soil type.

To extract the soils specific to barley fields in the province, the layer *Topsoil physical properties of Europe (based on LUCAS topsoil data)* (Ballabio et al., 2015) has been clipped in QGIS with the layer of the barley fields of the province identified through the *EUCROPMAP 2018* (d'Andrimont et al., 2021). The result show that more than three-fourths of these areas belong to the *Loam* textural class. To take into account the possible changes in areas used for growing barley through the years, this data has been double-checked through the *CORINE Land Cover Dataset,* by selecting the *Non irrigated arable land* areas from the 2006, 2012, and 2018 datasets (European Union's Copernicus Land Monitoring Service information, 2020c, 2020b, 2020a), considering that barley is the largest non-irrigated crop in the Almeria province, and the same process was repeated. The results of this second analysis confirm the information retrieved before.

Soil depth

The soil depth has been kept as default in AquaCrop-OSPy, at 1.2 meters, divided into 12 layers of 0.1 meters. Indeed, the maximum rooting depth of barley in AquaCrop-OSPy is 1.3 meters. Moreover, in AquaCrop-OSPy the bottom layer of the soil is programmed to expand in case the rooting depth of the plant exceeds the soil depth (Kelly & Foster, 2021b). For these reasons, the default value has been accepted.

Groundwater table

As set by default in AquaCrop-OSPy, the groundwater table has not been considered, since no specific information about shallow groundwater resources in the area was found (ESRI, 2022).

Crop characteristics

Crop parameters

The parameters selected to describe barley growth in the province of Almeria were the standard ones available in AquaCrop-OSPy (Kelly & Foster, 2021a), without applying any local calibration. These parameters are calibrated for the Tigray region in Ethiopia (Raes et al., 2023a). The variety represented by the parameters has a short cycle, which gives hints that it might be a spring one (Steduto et al., 2012). This introduces a significant approximation, since the cycle of barley will be modeled to be shorter than what is reported in the literature for the Almeria province (Steduto et al., 2012): with a harvesting date that will fall in mid-February rather than in June (Subsecretaría de Agricultura & Pesca y Alimentación, 2014). This has been accepted as a conservative approach to modeling because the crop's growth will happen in the wettest months of the year, thus possibly posing less water stress on the crop. It is however recognized that it will impact the results, and the specifics of this will be addressed in the *Discussion* chapter.

Calendar type

AquaCrop-OSPy allows the selection of two different barley parametrizations: one following calendar days, and the other one following thermal days, expressed as growing degree days (°C day) calculated as a subtraction between the crop's base temperature, and the average air temperature (Raes et al., 2023b).

It was chosen to use the growing degree days parametrization since it allows to see the effects of thermal regime changes on the crop and is the most suitable one to assess climate change impact (Steduto et al., 2012).

Sowing date

Following what was suggested by Russel (1990), and by the *Calendario de Siembra, Recoleccion, y Comercializacion* (Subsecretaría de Agricultura & Pesca y Alimentación, 2014)*,* the sowing date of barley in the Almeria province ranges between mid-October to mid-December. To find a suitable date to be inputted in AquaCrop as default for all the simulated years, different runs of the model have been programmed with sowing dates between the 15th of October and the 15th of December. The aim was to assess how much the results varied depending on this parameter. The results are shown in Figure 10. To evaluate the model's response under different water stress conditions, two cases have been modeled: with low initial soil water content (20% TAW), and with high initial soil water content (100% TAW).

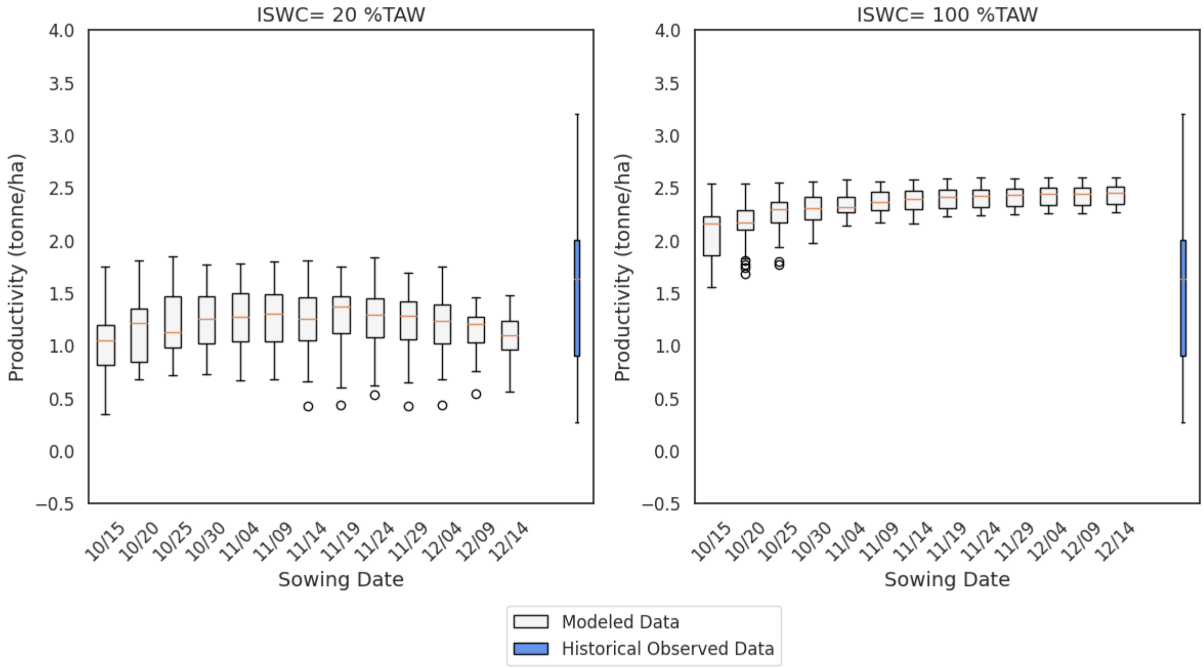

***Figure 10**. Sensitivity of AquaCrop-OSPy results to the sowing date. Results obtained with an ISWC of 20% TAW (left) and 100% TAW (right).*

These graphs show how a minimal difference exists between the results obtained with different sowing dates for both scenarios. Therefore, being in the middle of the possible sowing dates, and since in Figure 10, on the left, it is among the ones that give higher yields, the 10th of November has been selected as the reference sowing date.

Management practices

Soil fertility level

As suggested by de Roos et al. (2021), the soil fertility level has been set to 70%. This has been achieved through a crop recalibration for fertility stress through the Guided User

Interface (GUI) implementation of AquaCrop, since AquaCrop-OSPy does not explicitly allow setting a fertility level. Table 4 illustrates the crop parameters that have been changed.

Table 4. *Modified crop parameters to account for limited soil fertility.*

	Default	**70% soil fertility level**
CCx	0,8	0,48
WP	15	14,9
CDC	0,006	0,0001
CGC	0,0087	0,0083

Weed infestation and practices that affect the soil-water balance

Both parameters have been left as default, thus with no weed infestation, and with no practices that affect the soil-water balance. The former can indeed greatly change from year to year; since capturing its variability requires an amount of information that was not available, it has not been modeled. For the same reason, the latter were also left as default; only mulches have been modelled for future projections as an adaptation option, as will be explained later.

Irrigation strategy

The target crop of this thesis is rainfed barley, thus the irrigation strategy has been set to *Rainfed.* For future projections, however, irrigation has been modeled as an adaptation measure by setting various thresholds of soil water availability in the *Emergence* stage, triggering irrigation when reached. The choice of focusing only on this specific stage is in accordance with Russel (1990), who states that irrigation is more efficient in the early stages of barley's life cycle. The technical details of how this has been implemented will be addressed later in the work.

3.3 Retrieving the initial soil water content

Not having had access to direct information on the soil water content at the beginning of the growing season, and since AquaCrop-OSPy does not allow to run a continuous soil water balance, a way of estimating this crucial (Al-Bakri et al., 2011; Cammarano et al., 2019) parameter was necessary.

To solve this issue, after having defined all the main inputs as described in the previous section, different runs of the model were programmed with various ISWC for the baseline period (1985-2014). This parameter was expressed as a percentage of the Total Available Water (TAW): a parameter specific for each soil that represents the water held in the soil between its Field Capacity (FC) and the Permanent Wilting Point (PWP) (Datta, et al. 2017). It has been set to range from 0% TAW to 100% TAW, with intervals of 10%.

A statistical analysis was then conducted on the resulting yield distributions, to select the ones that better correlated with the historical observed data from the statistical yearbooks of crop yield from 1985 to 2014 (Ministero de Agricultura Pesca Y Alimentacion, n.d.). First, the basic hypothesis of normal distribution of the differences between the samples was verified through a Shapiro-Wilk test, with a significance threshold of 5%. Then, a paired t-test was conducted, as suggested by Sandhu & Irmak, (2019), to exclude the distributions that were significantly different from the observed historical one. The filtered distributions were then correlated with the historical observed distribution through a Spearman correlation coefficient, checking for monotonic correlation (Loughborough and Coventry Universities, n.d.-b), and a Pearson correlation coefficient, checking for a linear correlation (Loughborough and Coventry Universities, n.d.-a).

This was done repeatedly by applying rolling average windows of different sizes on the distributions, to assess what was the minimal period (window size) needed to capture barley growth trends in the province of Almeria using the proposed approach. Lastly, as suggested by Saldaña-Villota & Cotes-Torres (2021), the Root Mean Squared Error and the relative Root Mean Squared Error between the historical observed distribution and the modeled distributions obtained with the previously selected ISWC were calculated. Also in this case varying rolling average windows were applied, the aim was to assess which one of the modeled distributions minimized the errors, and how the magnitude of the error changes when different integration windows are considered.

The result of this process provided an indicative ISWC at the beginning of the growing season and was used to evaluate the climate change impact on rainfed barley in case of decreased soil water availability.

3.4 Setup of the AquaCrop-OSPy runs for climate change impact analysis

The following section explains how the different simulations with AquaCrop-OSPy have been programmed. It must be noted that, being the daily data from the different climate models asynchronous they cannot be averaged. Thus, AquaCrop-OSPy needs to be run singularly with each climate model, and the results of each run are then averaged to obtain an ensemble-averaged result for each year of simulation.

Baseline period: 1985-2014

Having defined all the required inputs, AquaCrop-OSPy was run for the baseline period from 1985-2014 to retrieve a reference dataset of yields for comparison with future projections. This dataset will have data for 29 years, rather than 30, because of the sowing date set on the 10th of November, which causes the first harvesting year to be 1986.

Future projections

To evaluate the impact of climate change on barley yields in the province of Almeria, projections for the two target time periods have been programmed in different ways to evaluate the different impacts of climate change and different possible adaptation pathways. The details related to each run are described as follows. All the results have been expressed in terms of percentual change from the mean of the baseline period, focusing on anomalies rather than absolute values. Table 5 summarizes the modelling options included in each run programmed.

Standard Run

First, a run has been programmed to assess the impacts that climate change will have on barley under the different SSP scenarios and time periods. To account for possible decreases in soil water availability at the beginning of the growing season, three sub-scenarios have been defined for each analyzed SSP scenario and timeline: one with the same initial soil water content as the baseline time period (30% TAW), one with 10% TAW, and one with 20% TAW.

Irrigation as an adaptation strategy

The first adaptation pathway tested through the model was irrigation. To model this, irrigation was imposed to be triggered when the soil water content dropped below a specified percentage of TAW. This threshold was set at different values for the four crop's life stages contemplated by AquaCrop-OSPy (emergence, canopy growth, max canopy, senescence), keeping it at zero for all the stages except the *Emergence* one, where, for each one of the scenarios and sub-scenarios described in the section above, the irrigation threshold was set first at 0% TAW and then at 20% TAW. Where a threshold of 0% TAW means that water is given to the plant every time it goes below the Permanent Wilting Point.

Mulches as an adaptation strategy

To assess the effectiveness of field management strategies to adapt to climate change and having assessed the crucial role of increased potential evapotranspiration in future scenarios, the adoption of mulches was modeled. This practice consists of covering the soil with organic material to reduce soil moisture loss. The modelling was done within the simulation framework defined in the previous section, aiming to see how this practice affected the irrigation demand and yield change. Within AquaCrop-OSPy, their presence has been modeled by indicating that 100% of the soil is covered with mulches, to assess their maximum possible impact on the results.

Changing sowing date as an adaptation strategy

Another adaptation strategy that was modeled is the change of the sowing date, as suggested by the Unión de Pequeños Agricultores y Ganaderos (2018). To do so, different runs of the model were programmed for all the different scenarios and sub-scenarios, but only under rainfed conditions and without the application of mulches. Planting dates were selected from the 15th of October to the end of November, with intervals every 10 days. The aim was to see if any clear pattern of improved yields was detectable through the data.

***Table 5**. Summary of the different options programmed within each run of AquaCrop-OSPy for the future projections. Each coloured cell must be read including all the cells behind to which it is linked.*

Time Period	**SSP Scenario**	**ISWC sub-scenario**	**Adaptation Pathway**		
			Irrigation Threshold	**Mulching**	**Change of sowing date**
Mid-century *or* End-century	SSP1-2.6, *or* SSP2-5.4, *or* SSP5-8.5	10% TAW	Rainfed	No	🟨 Yes
					🟩 No
			0% TAW	Yes	🟧 No
				No	🟦 No
			20% TAW	Yes	🟧 No
				No	🟦 No
		20% TAW	Rainfed	No	🟨 Yes
					🟩 No
			0% TAW	Yes	🟧 No
				No	🟦 No
			20% TAW	Yes	🟧 No
				No	🟦 No
		30% TAW	Rainfed	No	🟨 Yes
					🟩 No
			0% TAW	Yes	🟧 No
				No	🟦 No
			20% TAW	Yes	🟧 No
				No	🟦 No

Cluster of results to which each modeled run refers.

- 🟨 Changing sowing date
- 🟩 Climate change impact
- 🟧 Mulches performances
- 🟦 Irrigation needs

3.5 Presentation of results to local stakeholders and discussion

The results obtained have been presented to local stakeholders in Almeria on the 25th of January 2024 during a workshop organized within the RethinkAction project. The aim was to discuss about them and in general about the Rethink Action project to integrate local knowledge into the discussion. This allowed to frame the results into a wider framework and interpret the results in a more comprehensive way.

4. Results

The following section will present the results of the analysis illustrated above, with brief analytical comments to outline the main features that will be addressed in the *Discussion* section.

4.1 Initial soil water content analysis and comparison with the historical observed dataset

The first results produced concern the retrieval of the indicative initial soil water content to be used as a reference for future scenarios. Plus the statistical analysis to assess the relationship between modeled and historical observed data.

Indicative initial soil water content

Figure 11 reports the boxplots of the results of AquaCrop-OSPy for the baseline period (1985-2014), obtained with varying initial soil water contents, compared to the historical observed ones from the Spanish Ministry of Agriculture (Ministero de Agricultura Pesca Y Alimentacion, n.d.).

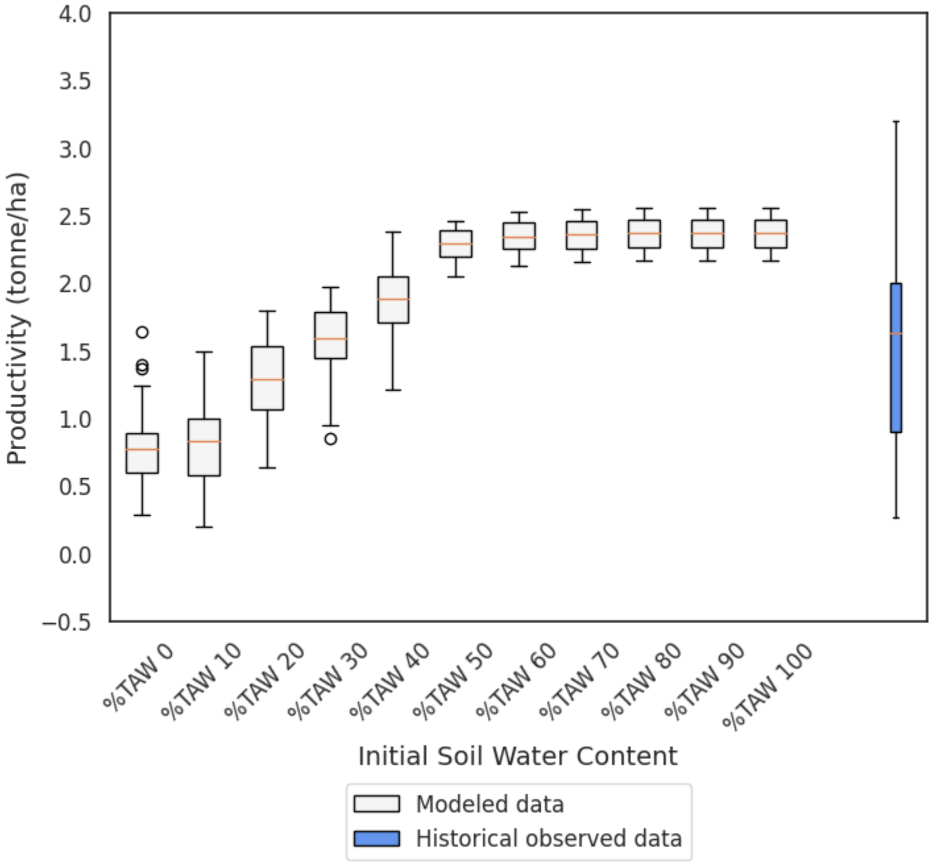

Figure 11. *AquaCrop-OSPy simulation results with different initial soil water contents, compared to the historical observed dataset.*

From the graph, it is possible to notice how the modeled results vary widely depending on the ISWC, especially when the values range from 10% TAW to 50% TAW. Moreover, while no modeled distribution has a variance comparable to the observed one, all the modeled distributions fall within the observed variance. A further feature worth mentioning is that no increase in yield is associated with initial soil water contents higher than 50% TAW; and that the results obtained with these higher initial soil water contents have a smaller variance as compared to the other results obtained.

Table 6 reports the p-values obtained with the paired t-test, in bold are reported the values higher than the selected significance threshold of 0.05, meaning that the correspondent values are not significantly different from the observed historical ones. From this analysis, the two values of initial soil water content that comply with the threshold are 20% TAW and 30% TAW, however, the results obtained with 40% TAW have a p-value comparable to 0.05, thus, also these results were selected for further analysis.

Table 6. *Results of the paired t-test carried out between modelled data and historical observed data.*

Initial Soil Water Content (%TAW)	p-value
0	0.000015
10	0.000081
20	**0.090279**
30	**0.820800**
40	**0.032492**
50	0.000014
60	0.000005
70	0.000004
80	0.000003
90	0.000003
100	0.000004

Correlation analysis

Figure 12, on the left, reports the Pearson correlation coefficient calculated between the historical observed data and the modelled data obtained with the three initial soil water contents selected before. The correlation coefficient has been calculated after having applied a rolling average operator with different window sizes (which can be seen on the X-axis) on the target datasets. Table 7 illustrates the p-values linked to each correlation coefficient calculated. A value lower than the significance threshold of 0.05 means that the correlation is significantly different from 0. The same information, but related to Spearman's correlation coefficient, is reported in Figure 12, on the right, and in Table 8.

The analysis of these graphs and tables indicates how a positive correlation (both with Spearman and Pearson) appears with a rolling average window of at least four years. The positive correlation becomes significantly different from zero only after 8 (Pearson), and 9 (Spearman) years of averaging window.

A peak in correlation appears with a rolling average window of 13 years, and the distribution that is better correlated with the historical observed one appears to be (especially for Pearson correlation) the one obtained with an initial soil water content of 40% TAW. Finally, it is interesting to notice how both graphs show the same trend, both in terms of correlation coefficients and in terms of p-values.

With regards to the values of the correlation coefficients, in both cases, with larger averaging windows, they reach values of "strong correlation" (equal or greater than 0.6), even reaching "very strong" values when exceeding 0.8. Before, the data stayed within the "moderate" correlation values, when being equal to or greater than 0.4 (Loughborough and Coventry Universities, n.d.-a, n.d.-b).

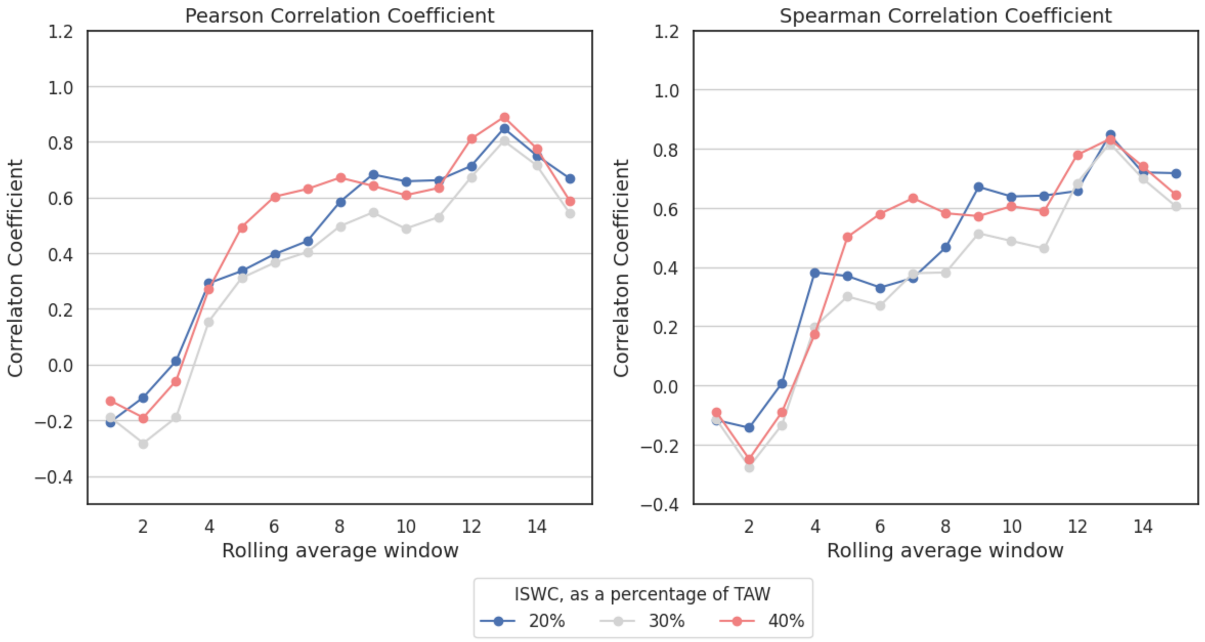

Figure 12. *Pearson (left), and Spearman (right) correlation coefficient with varying rolling average windows between modelled data and historical observed data.*

***Table** 7. P-values for the Pearson correlation coefficient obtained with different rolling average window sizes.*

Rolling Average Window	**20% TAW**	**30%TAW**	**40%TAW**
1	0.284557	0.323587	0.502231
2	0.550793	0.145711	0.331852
3	0.948099	0.342774	0.773144
4	0.147013	0.448486	0.179620
5	0.100353	0.129708	**0.012038**
6	0.054993	0.078831	**0.001802**
7	**0.034008**	0.055812	**0.001250**
8	**0.004245**	**0.018516**	**0.000623**
9	**0.000643**	**0.010385**	**0.001696**
10	**0.001589**	**0.028883**	**0.004399**
11	**0.002002**	**0.019713**	**0.003535**
12	**0.000885**	**0.002191**	**0.000044**
13	**0.000017**	**0.000101**	**0.000002**
14	**0.000798**	**0.001825**	**0.000404**
15	**0.006364**	**0.035858**	**0.020725**

***Table 8**. P-values for the Spearman correlation coefficient obtained with different rolling average window sizes.*

Rolling Average Window	**20% TAW**	**30%TAW**	**40%TAW**
1	0.545524	0.553215	0.644594
2	0.468331	0.157054	0.202283
3	0.968660	0.508111	0.656207
4	0.053747	0.328978	0.399001
5	0.068681	0.144034	**0.010503**
6	0.113775	0.201213	**0.002917**
7	0.088074	0.074140	**0.001177**
8	**0.028450**	0.079134	**0.004476**
9	**0.000860**	**0.017071**	**0.006657**
10	**0.002417**	**0.028772**	**0.004623**
11	**0.003035**	**0.045819**	**0.007905**
12	**0.003030**	**0.001738**	**0.000138**
13	**0.000017**	**0.000059**	**0.000033**
14	**0.001638**	**0.002535**	**0.001018**
15	**0.002581**	**0.016381**	**0.009215**

Comparison between rolling averaged historical observed data and modelled data

Figure 13 compares the historical observed and the modelled data, with a rolling average window size of 13 years, which was identified as the one that provided the best correlation. The main feature that emerges is that, while in the first part of the graph the historical observed data follows the rolling averaged data modeled with a 30% TAW initial soil water content, in the second half of the data the historical observed curve moves up and stays closer to the curve obtained with an initial soil water content of 40% TAW. The reasons for this shift in historical observed data might be many, and it is out of the scope of this thesis to analyze them. However, it is important to notice how the results obtained with 30% TAW are a mid-way approximation of the interval of possible initial soil water contents.

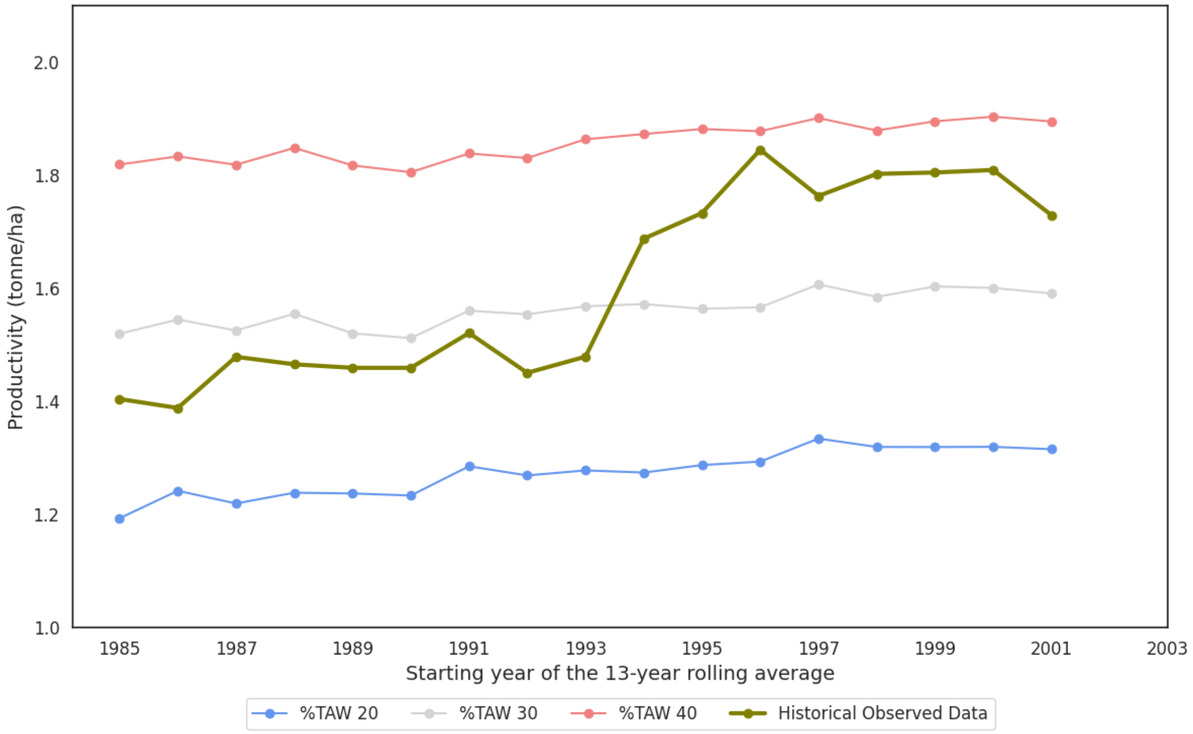

***Figure 13**. 13-year rolling averaged productivities. Modelled data compared to historical observed data.*

Root Mean Squared Error (RMSE) and relative Root Mean Squared Error (rRMSE)

Figure 15 shows respectively the Root Mean Squared Error and the relative Root Mean Squared Error between the modelled data obtained with the different selected ISWC values and the historical observed data, after having applied a rolling average operator with different sizes (X-axis) on both datasets.

The behavior of both graphs is very similar and two are the main features that come across. First, with larger rolling average windows the error decreases, in particular, the steeper decrease in error happens when the rolling average window ranges from 1 to 5 years. Second, the distribution obtained with a 30% TAW is the one that minimizes both RMSE and rRMSE for all the rolling average windows. With this dataset, it is possible to obtain a relative Root Mean Squared Error lower than 10% with larger rolling average windows, while with the other two datasets, the error is constant at around 20%.

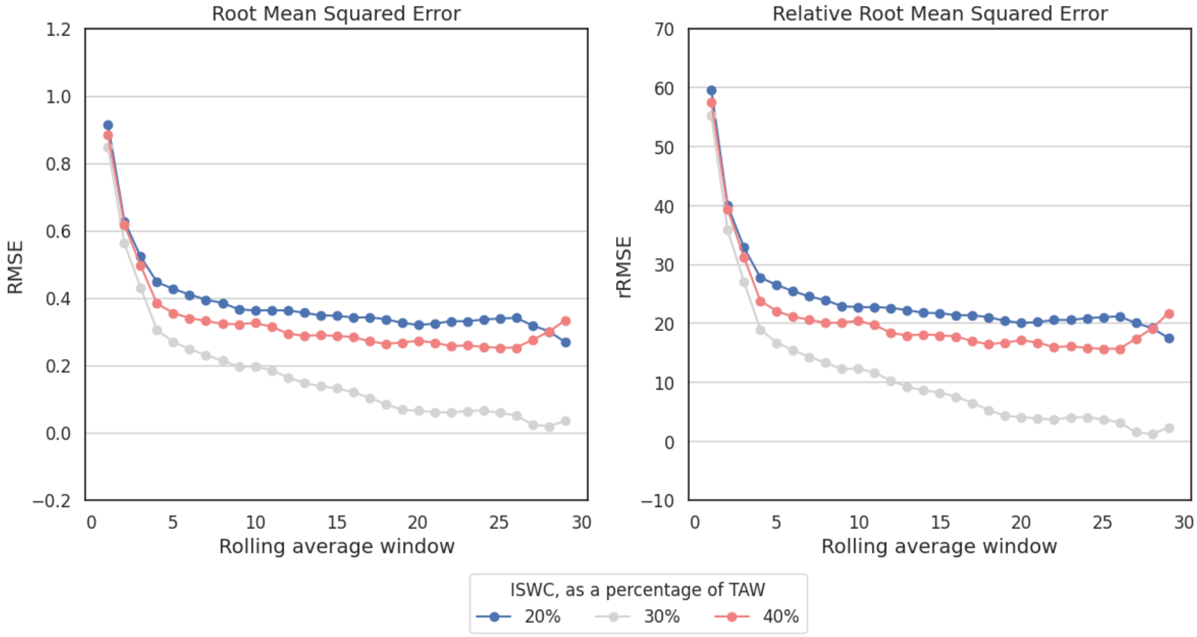

Figure 14. *Root Mean Squared Error (left), and relative Root Mean Squared Error (right) between modelled and historical observed data, calculated with different rolling average windows.*

4.2 Climate change impact on barley yields

Figure 15 depicts the impact of climate change on rainfed barley productivity in the province of Almeria at mid-century (2041 to 2070) and end-century (2071-2100) expressed as a percentual change from the mean of the modeled distribution of the baseline period. For both time periods, within each SSP scenario, three sub-scenarios of ISWC exist: 10% TAW, 20% TAW, and 30% TAW. Table 9 moreover numerically indicates the percentual changes in average for all the scenarios. Table 14A of the Appendix reports the same changes, but in terms of absolute values, and the average yields for each scenario (Table 15A). Figure 17A reports instead an alternative visual representation of the results used for communication purposes. In the tables, redder cells indicate greater losses, and greener cells indicate greater gains, also, values in bold are statistically significant according to a paired t-test with a significance threshold of 0.05.

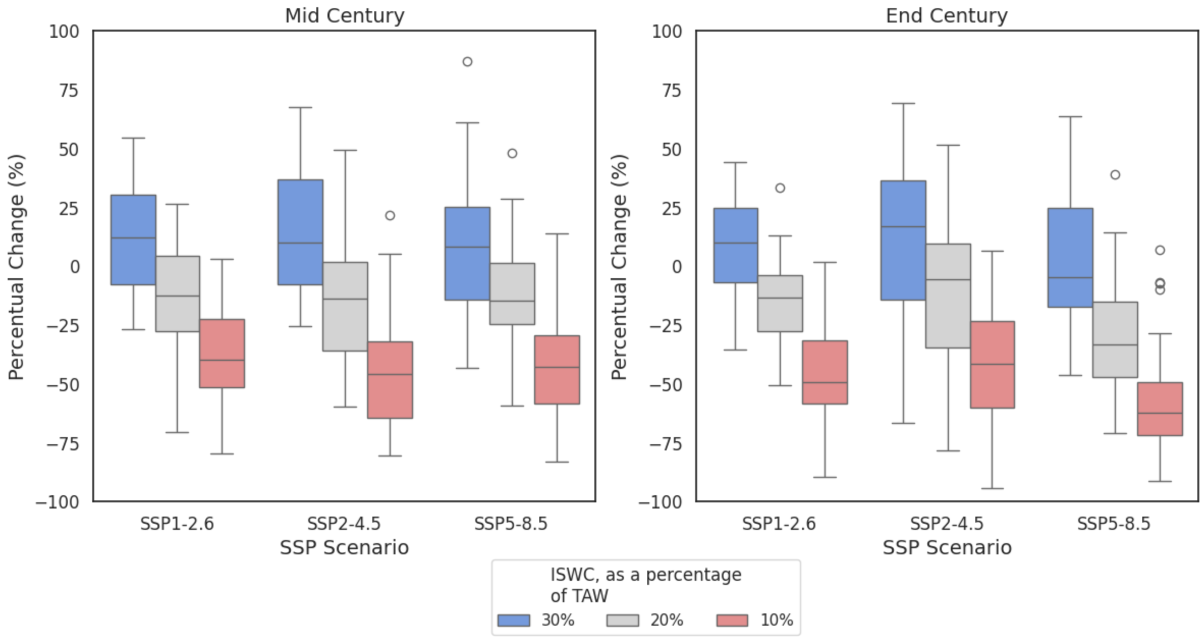

Figure 15. *Percentual change in rainfed barley productivity at mid-century (left) and end-century (right), under SSP1-2.6, SSP2-4.5 and SSP5-8.5. Results obtained with different initial soil water contents.*

Table 9. *Percentual changes in average productivity at mid-century and end-century, under SSP1-2.6, SSP2-4.5 and SSP5-8.5.*

	2041-2070			**2071-2100**		
ISWC	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	**-37,59**	**-42,98**	**-44,82**	**-45,90**	**-42,98**	**-55,15**
20% TAW	-12,10	-12,49	-12,87	-15,60	-10,40	**-27,59**
30% TAW	11,62	**14,03**	11,06	6,06	11,97	4,04

Mid-century: 2041-2070

What comes across from Figure 15, is that the most important difference in yield exists between initial soil water content sub-scenarios, rather than for constant initial soil water contents and different SSP scenarios. Indeed, while the change in yields across the different SSP scenarios is minimal, within a single one important differences exist depending on the initial soil water content.

Taking as an example SSP1-2.6, while with an ISWC at 30% TAW, the average yield can increase by around 14% (~ 0.2 tonnes/ha), with an initial soil water content at 10% TAW the average yield might be reduced of around -45% (~ 0.7 tonnes/ha), meaning an absolute difference of 60% between ISWC scenarios. On the other hand, by looking at how the results change throughout the SSPs for the same initial soil water content, it is possible to notice how the change is of just a few percentual points for all the initial soil water content scenarios. Overall, the lowest results seem to be associated with SSP5-8.5, with however minimal difference from SSP2-4.5.

End-century: 2071-2100

With regards to the differences among ISWC sub-scenarios and SSP scenarios, the behavior shown in Figure 15, on the right, is the same as mid-century, however, a more important differentiation between SSP scenarios appears, with SSP5-8.5 showing lower average yields for all the selected ISWC. Interestingly, the opposite trend exists for SSP2-4.5, with averages that slightly increase with respect to SSP1-2.6, and variances that expand, particularly for the 30% TAW and 20% TAW ISWC scenarios. Numerically speaking, the changes range from an increase of around 12%, with an ISWC of 30% TAW, up to -55% in the worst-case scenario of SSP5-8.5, and ISWC of 10% TAW. In absolute terms these changes approximately translate into + 0.2 tonnes/ha and -0.9 tonnes/ha.

SSP scenarios analysis

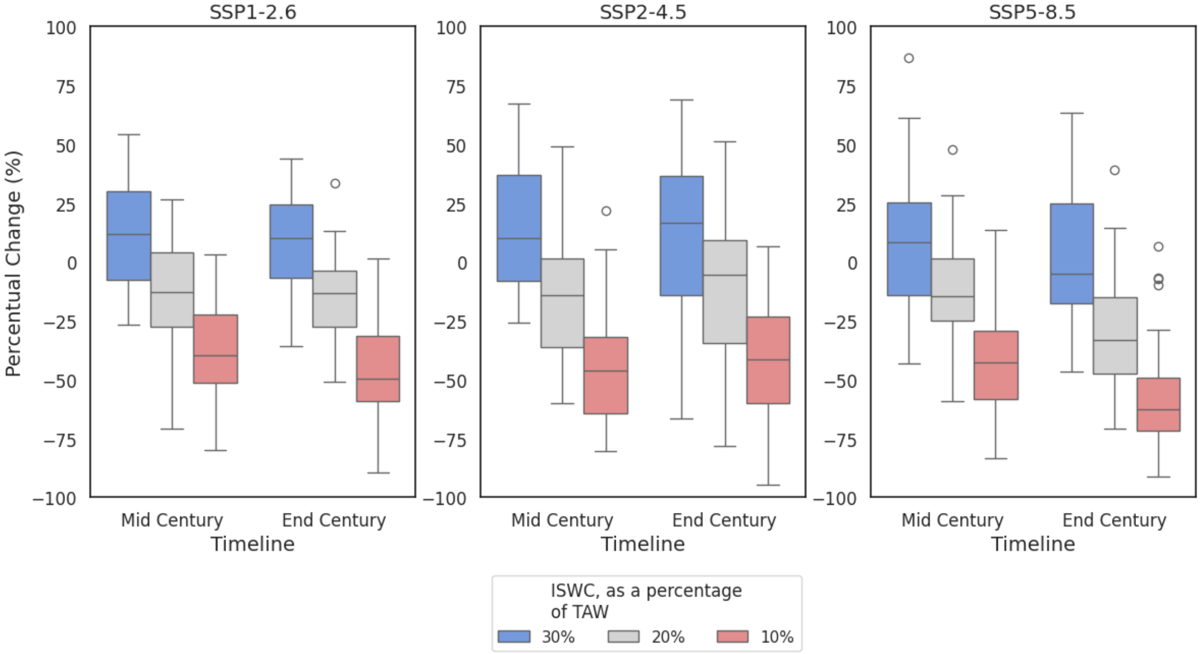

Figure 16. *Percentual change in productivity of rainfed barley under the analyzed scenarios. Results clustered by SSP scenario.*

Figure 16 depicts the evolution of SSP scenarios between mid-century and end-century considering different possible ISWC.

It is interesting to notice how three different behaviors exist among the three SSPs. First, for SSP1-2.6 there is not an important decrease between mid-century and end-century apart from an ISWC of 10%. Secondly. For SSP2-4.5 a slight positive change in productivity is projected at mid-century, compared to the end of the century. Third, under SSP5-8.5 the exact opposite trend exists, with productivity that shrinks in all the cases studied.

4.3 Adaptation options: irrigation and mulches

Yield change under different scenarios

Table 10 depicts the percentual average yield changes under the different pathways of adaptation modelled. Table 16A of the Appendix reports the same changes but in absolute values terms. Figure 18A of the Appendix graphically illustrates the results.

Table 10*. Percentual change in yields under different management options and climatic scenarios. Irr. Thrsh. = Irrigation Threshold; M = Mulches.*

ISWC Scenario	Management	2041-2070			2071-2100		
		SSP1-2.6	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	**No Irrigation**	**-37,59**	**-42,98**	**-44,82**	**-45,90**	**-42,98**	**-55,15**
	Irr. Thrsh. 0%	**-31,88**	**-37,54**	**-38,27**	**-40,38**	**-36,95**	**-44,90**
	Irr. Thrsh. 0% + M	**-29,39**	**-34,03**	**-35,20**	**-37,37**	**-34,80**	**-41,82**
	Irr. Thrsh. 20%	**17,63**	**21,07**	**20,24**	**12,36**	**21,05**	**20,32**
	Irr. Thrsh. 20% + M	**22,14**	**23,47**	**24,77**	**15,82**	**24,02**	**24,11**
20% TAW	**No Irrigation**	-12,10	-12,49	-12,87	-15,60	-10,40	**-27,59**
	Irr. Thrsh. 0%	-12,10	-12,49	-12,87	-15,60	-10,40	**-27,59**
	Irr. Thrsh. 0% + M	-7,55	-7,49	-8,32	-11,58	-6,34	**-21,75**
	Irr. Thrsh. 20%	7,90	10,81	6,44	2,90	7,76	2,23
	Irr. Thrsh. 20% + M	**13,25**	**15,25**	13,32	7,98	13,70	8,69
30% TAW	**No Irrigation**	11,62	**14,03**	11,06	6,06	11,97	4,04
	Irr. Thrsh. 0%	11,62	**14,03**	11,06	6,06	11,97	4,04
	Irr. Thrsh. 0% + M	**15,05**	**17,43**	**15,40**	**10,14**	**15,90**	9,52
	Irr. Thrsh. 20%	11,99	**14,29**	11,63	7,06	12,99	5,86
	Irr. Thrsh. 20% + M	**15,38**	**17,69**	**15,97**	**10,95**	**16,91**	11,27

It is possible to see how all the cases where initial soil water content was set to 10% TAW give both the greatest losses, and the greatest gains (in the case of irrigation threshold at 20% TAW). In this case, values of yield change are almost constant throughout all the SSP scenarios and time periods, with the only exception of SSP1-2.6 at the end of the century. Here, it appears that the increase in yield linked to an irrigation triggered by a threshold of 20% TAW is slightly lower than what is obtained in other scenarios. Moreover, all the changes in yield obtained in this ISWC scenario are statistically significant.

On the other hand, the results linked to a 20% TAW ISWC show limited changes both in terms of gains and losses, with only five significant changes: two significant increases at mid-century and with an irrigation threshold of 20% TAW coupled with the use of mulches, and three significant decreases, linked to SSP5-8.5 at the end of the century.

Concerning the results linked to a 30% TAW initial soil water content, all the changes obtained are positive, and the significant ones are mainly related to SSP2-4.5 at mid-century. Significant changes also happen for all the scenarios except SSP5-8.5 at the end of the century, when irrigation is triggered when soil water content drops below 0% and 20%, while mulches are adopted.

Overall, the greatest losses, and lower gains, happen at end-century, particularly for SSP1-2.6 and SSP5-8.5. This trend seems particularly marked for the results obtained with 20% TAW and 30% TAW initial soil water content.

Lastly, from Table 16A, it is noticeable how these percentual changes translate in absolute changes that never exceed 1 tonne/hectare, and rarely exceed 0.5 tonne/hectare, only for negative changes.

Irrigation water needs

Table 11 shows the seasonal irrigation needs, in terms of m³ per hectare. This Table indicates how greater irrigation needs are linked to a lower initial soil water content, and a higher irrigation threshold. While for an initial soil water content of 10%, irrigation is required for all the scenarios (thus also for a threshold of 0% TAW where water is needed to avoid going below the Permanent Wilting Point), an initial soil water content of 30% TAW only requires minimal amounts of water, and only with an irrigation threshold set at 20% TAW.

Table 11. *Irrigation needs under different management options and climatic scenarios (m³/ha). Irr. Thrsh. = Irrigation Threshold; M = Mulches.*

		2041-2070			2071-2100		
ISWC Scenario	**Management**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	**No Irrigation**	0,00	0,00	0,00	0,00	0,00	0,00
	Irr. Thrsh. 0%	48,03	55,42	80,05	55,42	71,43	109,61
	Irr. Thrsh. 0% + M	38,18	50,49	75,12	48,03	65,27	97,29
	Irr. Thrsh. 20%	355,91	364,53	386,70	364,53	376,85	396,55
	Irr. Thrsh. 20% + M	344,83	346,06	370,69	349,75	360,84	376,85
20% TAW	**No Irrigation**	0,00	0,00	0,00	0,00	0,00	0,00
	Irr. Thrsh. 0%	1,23	4,93	6,16	3,69	11,08	13,55
	Irr. Thrsh. 0% + M	1,23	3,69	3,69	2,46	9,85	11,08
	Irr. Thrsh. 20%	229,06	232,76	236,45	233,99	233,99	243,84
	Irr. Thrsh. 20% + M	226,60	227,83	236,45	230,30	231,53	240,15
30% TAW	**No Irrigation**	0,00	0,00	0,00	0,00	0,00	0,00
	Irr. Thrsh. 0%	0,00	0,00	0,00	0,00	0,00	0,00
	Irr. Thrsh. 0% + M	0,00	0,00	0,00	0,00	0,00	0,00
	Irr. Thrsh. 20%	7,39	2,46	7,39	7,39	12,32	14,78
	Irr. Thrsh. 20% +M	6,16	2,46	7,39	6,16	12,32	13,55

Concerning the two analyzed time periods, it appears that at the end of the century, irrigation needs are slightly higher, with similar increases across all SSP scenarios. The largest differences among SSP scenarios are linked to an initial soil water content of 10% TAW, and overall, the greatest irrigation needs happen in scenario SSP5-8.5 at the end of the century.

Mulches efficiency

In Table 12 it is reported the effect of mulches on both irrigation needs and yields. Figure 19A reports the same results but graphically. The results are indicated in terms of percentual change with respect to the corresponding scenarios modeled without mulches. The overall trend is that mulches bring gains in terms of yield, and reduced irrigation needs, specifically, while the gains in yield never exceed 10%, and only in a few cases exceed 5%, for what concerns irrigation needs, the reduction widely exceeds 10%, even reaching values of -20% and a peak of -40%.

Regarding overall patterns, no clear signal appears, and the impact of mulches is almost equal among all the cases analysed, with the only exception of SSP5-8.5 at the end of the century, where efficiencies slightly increase in all the scenarios of initial soil water content.

One important thing to notice is that the percentual performances of mulches translate into low absolute values of yield gain, as can be seen in Table 17A of the Appendix, but into more important absolute performances for irrigation needs reduction, with a maximum of almost 20 m^3/ha spared.

***Table 12**. Mulches percentual impacts on irrigation needs and yields under the different analyzed adaptation pathways. Irr. Thrsh. = Irrigation Threshold; Y.I. = Yield Change; I.D.C. = Irrigation Demand Change.*

		2041-2070			2071-2100		
ISWC Scenario	**Management**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	**Irr. Thrsh 0% - Y.I.**	2,50	3,51	3,08	3,01	2,15	3,08
	Irr. Thrsh 0% - I.D.C.	-20,51	-8,89	-6,15	-13,33	-8,62	-11,24
	Irr. Thrsh 20% - Y.I.	4,51	2,40	4,53	3,46	2,98	3,79
	Irr. Thrsh 20% - I.D.C.	-3,11	-5,07	-4,14	-4,05	-4,25	-4,97
20% TAW	**Irr. Thrsh 0% - Y.I.**	4,55	5,00	4,55	4,01	4,07	5,84
	Irr. Thrsh 0% - I.D.C.	0,00	-25,00	-40,00	-33,33	-11,11	-18,18
	Irr. Thrsh 20% - Y.I.	5,35	4,44	6,88	5,08	5,94	6,46
	Irr. Thrsh 20% - I.D.C.	-1,08	-2,12	0,00	-1,58	-1,05	-1,52
30% TAW	**Irr. Thrsh 0% - Y.I.**	3,43	3,40	4,33	4,09	3,93	5,48
	Irr. Thrsh 0% - I.D.C.	0,00	0,00	0,00	0,00	0,00	0,00
	Irr. Thrsh 20% - Y.I.	3,39	3,40	4,33	3,90	3,93	5,42
	Irr. Thrsh 20% - I.D.C.	-16,67	0,00	0,00	-16,67	0,00	-8,33

4.4 The effect of changing the sowing date

Finally, Table 13 reports the percentual changes in yield obtained by sowing barley at different planting dates between the 15th of October and the end of November under rainfed conditions, compared with the yield obtained under the same conditions, and for each scenario, but while sowing on the 10th of November. Also here, in the Appendix (Figure 20A), are reported the results visualized in a graphical way.

Table 13. *Percentual change in yield with respect to rainfed conditions with sowing on the 10th of November.*

		15/10	25/10	04/11	14/11	24/11
Timeline	**ISWC Scenario**	**SSP1-2.6**				
Mid Century	**10% TAW**	-4,1	1,0	9,9	-2,1	-8,2
	20% TAW	-0,8	3,1	9,2	2,8	3,7
	30% TAW	-7,9	-4,3	3,4	2,3	2,6
End Century	**10% TAW**	-2,8	10,0	15,5	2,6	-10,7
	20% TAW	-6,7	3,1	4,4	1,9	-1,1
	30% TAW	-12,0	-12,0	4,2	3,4	0,4
		SSP2-4.5				
Mid Century	**10% TAW**	1,8	14,0	9,6	2,6	-9,1
	20% TAW	-4,6	10,6	6,8	-12,0	-2,6
	30% TAW	-3,0	0,7	3,3	2,0	-3,0
End Century	**10% TAW**	-3,4	6,9	10,6	4,5	-2,4
	20% TAW	-7,3	0,2	5,9	4,2	-2,8
	30% TAW	-11,2	-1,5	3,3	5,0	1,1
		SSP5-8.5				
Mid Century	**10% TAW**	3,7	12,6	12,3	1,0	-5,4
	20% TAW	-6,2	3,0	5,3	0,9	-1,7
	30% TAW	-9,2	0,9	3,3	0,8	-1,3
End Century	**10% TAW**	-14,4	-3,8	7,5	4,7	0,5
	20% TAW	-10,3	-1,6	13,0	13,8	0,5
	30% TAW	-17,8	-4,3	4,2	3,4	-2,4

The main feature that can be outlined is that the absolute value of changes rarely exceeds 10% and that there is not a clear pattern in increased yields associated with earlier or later sowing dates. Indeed, it seems that the best sowing date for all the scenarios remains around the reference one, with a slight preference for the indicative date of the 4th of November. Furthermore, greater gains and lower losses seem to be associated with the mid-century timeline. On the other hand, at the end of the century, it seems that greater losses in yield are linked to a sowing date that is outside the ideal window, especially within SSP5-8.5, which is also the scenario that seems to be the most important to correctly select the sowing date to have optimal yields. Also, greater losses are associated with earlier sowing dates, rather than later sowing dates. A last feature that can be pointed out, is that with higher initial soil water contents, the variance in results is reduced.

4.5 Results from the stakeholders interaction in Almeria

From the stakeholders interaction in Almeria mentioned in Chapter 3.5 three themes relevant for the proposed work emerged:

1. The will of the province to reduce the impact on water resources and restore natural water reserves available in the province's territory.
2. The increasing investments and shifting towards the use of desalinated water and restored wastewater for agricultural porpuses.
3. The issue of migration within the province from the inland to the cost incentivized by agricultural development. Leading to reduced development of rural areas and depopulation.

From these few pints emerges clearly the cruciality of the water issue in Almeria. Also, the third point underlines the importance of agriculture for the development of the Province, and the issues that can arise from intensive greenhouse agriculture.

5. Discussion of results

This section presents a discussion of the results illustrated before, aiming at answering the proposed research questions and linking the results to what is outlined in the *Literature review*.

5.1 Linking back to the research questions

How well-suited is the standard AquaCrop barley crop parametrization to model multi-year trends in rainfed barley production in the Almeria province?

Results show that all the distributions linked to each initial soil water content reported in Figure 11 fall within the variance of the historical observed dataset. This increases the confidence that the model can give realistic results while modeling barley growth in the Almeria province, even with the provided inputs and the uncalibrated barley parameters. The variance of the observed historical data being so large can be linked to a variety of factors that the model is not able to capture, such as pests and diseases, as mentioned by Steduto et al., (2012). Or to events that the model is not able to capture when run with the provided inputs. Moreover, as mentioned by Russel (1990) in arid areas barley sowing happens based on rainfall criteria, rather than on a specific date. Therefore in case of greater precipitations (or greater infiltration) soil water content can be higher than average and cause higher yields, explaining the great variance in the historical observed data, and suggesting that results obtained with different initial soil water contents can mirror particularly wet years.

The approach developed throughout this work aimed at identifying a suitable initial soil water content to use as a reference for the analysis of future scenarios. This after having acknowledged the importance of this parameter for rainfed barley cropping in the Mediterranean from Cammarano, et al., (2019), and Al-Bakri, et al. (2011). Three suitable candidates were identified through a paired t-test on the distributions and further analyzed. These initial soil water contents corresponded to 20% TAW, 30% TAW, and 40% TAW. It is worth remarking once again that these values do not represent the actual initial soil water content at sowing for barley, rather, these are the ones that provide the yield distributions that better correlate to the historical observed ones. Thus they can be interpreted as an indicative average initial soil water content at which farmers sow barley after having fixed all the other variables.

To select the more suitable initial soil water content to use as a reference, a statistical analysis was carried out. In this process, the approach based on increasing rolling average windows was applied to understand the minimum window of time that the proposed methodology can model while providing meaningful results. First, it has been analysed the evolution of the correlation coefficient between the modeled yields and the historical observed yields. As mentioned in the previous chapter, a minimum window of indicatively 10 years is needed to capture a significant positive correlation between the modeled and the historical observed datasets. Interestingly this happens for both Pearson's and Spearman's correlation coefficients, indicating the presence of a positive monotonic linear correlation between the datasets (Loughborough and Coventry Universities, n.d.-a, n.d.-b). This supports the hypothesis that the proposed approach can be used to capture multi-year trends of rainfed barley growth in the province of Almeria. It however needs to be acknowledged the fact that for smaller averaging windows (less than 4 years), the correlation coefficients calculated with both methods are negative. This gives strong indications in the direction that the proposed approach is not suitable to capture multi-year variability, as expected due to the approximations made in terms of inputs. Indeed, as it is possible to see in Figure 6, rainfed barley production has an important inter-annual variability, which can be caused by different factors that AquaCrop cannot model if provided with low accuracy inputs as in this study (Steduto et al., 2012).

It is furthermore interesting to analyze the error linked to the modeled yields, as reported in Figure 14. It is immediately evident how the results obtained with a 30% ISWC are the ones that reduce the error the most, allowing it to go below 10% for larger rolling average windows, and showing how with an increased window size the error further decreases. This indicates that the performance obtained by running the model with a 30% TAW ISWC is markedly better than what can be achieved with the other initial soil water contents. This gives indications to support the selection of 30% TAW as the reference initial soil water content. The hypothesis is also supported by what is shown in Figure 13, where it is evident how results obtained with a 30% TAW initial soil water content constitute an “in the middle” projection of yields. Indeed, the curve relative to the historical observed data is well represented by the above-mentioned modeled curve for the first half of the graph, before it moves at higher values, closer to the curve obtained with an initial soil water content of 40% TAW. It is interesting to highlight how it seems to be contemporary to the steep reduction in sown areas and total production shown in Figure 6. The reasons that caused this shift in productivity might however be various, and it is out of the scope of this work to investigate them.

To conclude and answer the first research question, because of the reasons illustrated in the previous paragraphs, namely:

- the significant positive correlation between modelled and historical observed data that emerges when averaging at least 10 years of data.
- the low Root Mean Squared Error and relative Root Mean Squared Error.
- the not significant difference between modeled and historical observed yields, that arises when suitable initial soil water contents are selected.
- that all the possible distributions obtained from AquaCrop-OSPy by changing the initial soil water contents are included within the variance of the modeled historical dataset.

The uncalibrated barley parametrization available in AquaCrop-OSPy can be used to model multi-year trends in rainfed barley production. However, provided that the minimum time window needed is indicatively 10 years and that a relative Root Mean Squared Error of ~10% will be expected on the results. Importance must be put on initial soil water content, since it can largely affect the results, and, in case field data are not available, it is suggested to adopt the proposed methodology to obtain a reference ISWC to be used as a starting point for future projections.

What are the projected trends of rainfed barley yield change at mid-century (2041-2070), and end-century (2071-2100), under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios?

From what emerges in Figure 15, the scenario that will have the greatest impact on rainfed barley production is SSP5-8.5, particularly at the end of the century. The results are highly dependent on initial soil water content: for a high ISWC of 30% TAW the yields are projected to increase, the other cases instead project decreases. This consideration highlights the importance of this parameter for barley cropping in the Mediterranean, as already indicated by Cammarano, et al. (2019), and Al-Bakri, et al., (2011).

Indeed, a loss of initial soil water content up to 10% TAW might translate into a maximum loss in average productivity up to -55%. Such average change is instead between -10% and -27% for an initial soil water content of 20% TAW. The variances of the various distributions however largely overlap, indicating a minimal difference between the SSP scenarios and different time periods. This behavior can be linked to the climatic projections outlined in Figure 8, remembering that SSP1-2.6 and SSP2-4.5 do not show a marked difference, especially for what concerns precipitation. On the other hand, SSP5-8.5 has a behavior different from the other two, particularly from 2070 onwards. This can possibly explain the closeness in the results obtained with the different SSPs at mid-century, and the fact that at the end of the century SSP5-8.5 shows increased difference from the others.

The different SSP scenarios can also help to assess the different initial soil water content sub-scenarios. Even though the data available did not include projections of soil water, not allowing to indicate any ISWC as more probable than the others, Figure 9 provides evidence to support the hypothesis that on average, this parameter will decrease in time. Furthermore, the decrease in the difference between precipitation and potential evapotranspiration changing through the SSP scenarios suggests that certain ISWC sub-scenarios might be more tied to a specific SSP scenario than the others. The analysis linked to initial soil water content can have greater levels of complexity than the one proposed in this work, however, this research confirms the importance of this parameter, as found by Cammarano, et al. (2019) and Al-Bakri, et al., (2011).

It needs to be mentioned that the barley variety used in this study having a short life cycle will affect the results. This variety is indeed projected to be harvested in February, thus, it will only experience the wettest months of the year, as reported in Figure 4, and this will have an impact on the results in terms of absolute yield. However, as per the discussion of the previous section, there is confidence that the proposed analysis can capture the trends in increase or decrease of yields through time, providing suitable indications of future trends.

Linking back to the literature, these results are backed up by what was found by Bento, et al. (2021) for the Iberian Peninsula. The researcher illustrates how the radiative scenarios RCP8.5 and RCP4.5 (the same linked to SSP5-8.5 and SSP2-4.5) cause losses in barley production under a no-adaptation scenario at mid-century. For the numerical values obtained in this study, a good reference for comparison is provided by Cammarano, et al. (2019), who at mid-century, and for an RCP4.5 scenario indicate mean yield changes for barley in the Mediterranean basin to range between -27% up to +8%, depending on the "wetness" of the scenario. These results are comparable with what was obtained under SSP2-4.5 (the scenario with the same radiative forcing as RCP4.5) at mid-century: +12% to – 42%. The results are moreover comparable with the yield changes estimated by Al-Bakri et al., (2011) for barley yield change in Jordan in 2050: between +5% and -51%. Al-Bakri, et al. (2021) also indicates a grain yield change ranging (depending on the various analyzed locations) from +6% down to -17% under an RCP4.5, between 2030 and 2050, and from +30% to -27% under the same RCP but between 2080 and 2100. The respective results, but for RCP8.5 range instead from -9% to -58% (2030-2050), and +11% to -40% (2080-2100).

Overall the projected yield changes range from +14% to -45% at mid-century, and +12% and -55% at the end of the century, largely depending on the initial soil water content rather than the SSP scenario and the time period. From this, it can be concluded that while the different SSP scenarios will impact rainfed production in the future, especially under SSP5-8.5 at the end of the century, the variable that needs to be monitored with a greater degree of attention is the soil water content at the beginning of the growing season, since it can cause the greatest losses in yield in all the analyzed scenarios.

When using irrigation as an adaptation strategy, what will be the irrigation demand for barley in the analyzed scenarios and how will this affect yields?

Having acknowledged the importance of soil water content, the first adaptation pathway analyzed was irrigation. This was modeled only for the first stage of the crop cycle (*emergence*), as suggested by Russel (1990). To have an indication of a possible range of irrigation requirements, two thresholds were set to trigger irrigation: when soil water content dropped below 0% TAW (simply avoiding going below the Permanent Wilting Point and causing the crop to start dying), and when it dropped below 20% TAW (to keep a higher level of soil moisture throughout the early stages of barley growth).

The results indicate that irrigation needs will, as expected, be higher in cases of lower initial soil water content, and cases with a higher irrigation threshold. This will indeed cause the soil water content to drop below the threshold more often, triggering more irrigation events and thus increasing the irrigation needs.

Once again, the importance of the initial soil water content appears to be greater than the SSP scenario, or the timeline. In fact, in Table 11, while horizontally (changing SSP scenario and time period for the same field management strategy) the change is minimal, vertically it is much more important. This is both through different field management practices for the same ISWC scenario, and through the different field management practices but changing initial soil water content. In the latter case, while for an ISWC of 10% TAW and 20% TAW, the water needs are of a comparable order of magnitude, for an initial soil water content of 30% TAW, these shrink by two magnitude orders. This constitutes another indication in the direction that soil water content is a parameter of crucial importance for future projections of barley yield, and that preserving it is fundamental for the adaptation to climate change.

With regards to the impact of irrigation on yields, it is possible to notice how (as expected) increased irrigation causes increased yields: the scenario which has more important irrigation needs, thus the 10% TAW initial soil water content with 20% TAW irrigation threshold, is also the one that provides a greater increase in yields, reaching values that exceed +20%. The water needs, in this case, are greater than 300 m^3/hectare, which, multiplied by the hectares sown for barley in 2019 reported in Figure 6, result in ~ 3 hm^3 of water, representing around 1.5% of the yearly groundwater resources available in Almeria in 2022, and around 3% of the yearly superficial water resources of Almeria in 2022, according to the hydrological planification (Junta de Andalucia, 2023). These percentages are however projected to increase in the future due to reduced water availability, and the will to limit the exploitation of natural water resources and shift towards the use of desalination (Junta de Andalucia, 2023). The amount of water needed for adaptation in the future might therefore not be extremely severe, however, it will also not be negligible, especially if considering the development of the province, with the increased importance of greenhouses. This will therefore ask for decisions on if and how to allocate water resources to other kinds of agriculture, such as barley cropping.

However, if the will is to reduce water needs to the minimum, in the case of ISWC at 10% and an irrigation threshold at 0% (only giving water to avoid going below Permanent Wilting Point) the yield losses would exceed 30%. On the opposite side lays the 30% TAW initial soil water case, which brings good increases in crop productivity with extremely low water requirements; however, as shown in Figure 16, a case in which initial soil water content stays constant in the future is not supported by evidence from climate projections.

A "middle of the road" case is the one linked to a 20% TAW initial soil water content, with minimum losses in yield with a low irrigation threshold, and with small increases in yield for a higher irrigation threshold. In this latter case, however, the irrigation requirements are still over 200 m^3/hectare. Also, in this case, the results obtained for an irrigation threshold of 0% TAW, and not coupled with the use of mulches, yield the same results as a rainfed scenario, making the irrigation water provided in this scenario ineffective to face climate changes.

Overall, it seems that an ideal threshold for irrigation to maintain productivity constant can be found between 0% TAW and 20% TAW. Going into further detail to find a more specific threshold was not implemented. Such a process would indeed result in a value that would not make sense in a practical way: as discussed before, the approximations made throughout the process only allow retrieving indications of patterns and trends, and not specific values. Moreover, irrigation (unless in highly technological systems) does not happen based on thresholds of soil water content but rather happens based on farmers' knowledge. Therefore, indicating a specific threshold as a reference for future irrigation strategies would mimic a practice that is not implemented in reality.

To answer the question, the irrigation needs projected largely vary depending on the initial soil water content, the SSP scenario, and the aim of irrigation. To improve yields the irrigation water needed is indicated to exceed 300 m^3/hectare under a low initial soil water content scenario (10% TAW) and exceed 200 m^3/hectare with an initial soil water content of 20% TAW. Thus, lower amounts of irrigation water seem suitable for maintaining yields unchanged, however, simply providing water to avoid reaching Permanent Wilting Point does not seem to be suitable to avoid yield losses in cases of reduced ISWC. Overall, the irrigation threshold indicated for adaptation purposes should indicatively be looked for between 20% TAW and 0% TAW.

How will the application of mulches affect irrigation needs and yields?

Table 11 shows how the application of mulches effectively reduces irrigation needs and increases productivity. However, even though the percentual cover of the terrain by mulches was set to 100%, such impact is not particularly high. Nevertheless, being the indications positive, it can be concluded that applying this kind of field management strategy can be advised to adapt to climate change, as suggested by the Unión de Pequeños Agricultores y Ganaderos (2018). This strategy, moreover, by promoting *"agricultural practices that improve adaptation to climate change and resilience"* falls within the Strategic Pathway AC2, outlined by the Junta de Andalucía. Consejería de Agricultura Ganadería Pesca y Desarrollo Sostenible (2021), in the *Plan Andaluz de Accion Por El Clima;* and it moves in the direction outlined by the studies of Al-Bakri, et al. (2011) and Cammarano, et al. (2019) of preserving soil water content.

A last thing to remember is that, since the barley parametrization used has a shorter cycle, which only captures winter months, in the proposed analysis only the months with limited potential evapotranspiration are included, not allowing to see the real potential of this field management solution.

How will changing the sowing date impact rainfed barley yields?

Changing the sowing date is among the adaptation measures proposed by the Unión de Pequeños Agricultores y Ganaderos (2018), and its effectiveness for rainfed barley growth in the Almeria province was verified in the presented work as explained in Chapter 3. The results of this operation, reported in Table 12, indicate that there is no clear pattern that suggests how earlier or later sowing can benefit rainfed barley yields. Rather, they indicate how the window that allows to have an optimal yield becomes smaller when the stress for the plant is higher. This seems to capture the erratic behavior of rainfall caused by climate change (Ali et al., 2022), shortening the window of time where the plant gets enough rainfall water to grow in the earlier stages, and making the losses caused by sowing at other times more important.

The presented results, however, can only capture the effects that rainfall has during the crop's growth, and not those before sowing, when it accumulates in the soil and creates the preconditions for sowing. This can affect the sowing date to a significant extent: considering valid the indication by Russel (1990) of at least a cumulative 25 mm of rainfall needed before sowing, this condition might be verified at different times in the future, pushing the sowing date later. The possibility of not verification of ideal conditions for sowing was modeled in this study by setting different initial soil water contents: hypothesizing sowing to happen either with the same soil water content as the baseline scenario (30% TAW), or with soil water content deficit at sowing (20% TAW and 10% TAW) where the “ideal” condition of initial soil water content is not verified, and sowing is forced in dryer conditions.

It is interesting to notice how cases in which the soil water content at sowing has higher values produce results with lower variability, especially at mid-century. This indicates how soil water content is a crucial parameter not only for reducing losses in yield, but also for having more forecastable and constant results, allowing for easier planning of agriculture.

These results differ from what outlined by Cammarano, et al., (2019), who claim that changing the sowing date is a viable adaptation option to minimize the impacts of climate change. However, Cammarano, et al., (2019) explicitly considered cumulative rainfall before sowing as a parameter, adding a variable that was not modeled in this study. Moreover, their research focused on a few case study areas, and the results are different across locations. Also, it is important to remember that the results obtained by Cammarano, et al., (2019) only focus on a mid-century time period, and an RCP4.5, limiting the possibility of comparison to only a part of the results obtained in this study.

5.2 Implications of results

The information, results, and indications described in this work have as a target audience policymakers and decision-maker. The intent is to provide valuable information to drive provincial development. The results are indeed not accurate enough on an inter-annual basis to be of interest at the field and farm level (thus to farmers). But provide indications of future trends. This section suggests a possible analysis of the results and their implications for the Almeria province development, and it is largely based on the insight gathered from local stakehlders in Almeria, the results of which are summarized in Chapter 4.5.

The first indication that emerges from the results discussed previously is the crucial importance of monitoring and preserving soil water content, both for planning adaptation strategies and for mitigating the impacts of climate change on yields. Evidence shows indeed a large variability in results linked to this parameter, therefore suggesting that actions should be taken to preserve the water availability in the soil.

In general, even though losses in yields can be very high, the results show how barley cropping in the future could still be viable, especially if adaptation actions are undertaken. The most straightforward and effective adaptation pathway is irrigation: the evidence reported in this thesis shows how it could be possible to implement it without impacting excessively on the water resources balance of the province. Coupling this practice with mulches might moreover reduce such irrigation needs, making it more feasible to be applied. Implementing this adaptation solution is, however, resource intensive, requiring water, a critical resource in Almeria. Irrigation needs can be significantly reduced by ensuring a good soil water content at sowing. Therefore, it can be suggested to undertake this adaptation pathway only after having acted in the way of limiting soil water loss.

It needs to be mentioned that adaptation solutions that can, and might, be implemented are linked to different developing possibilities for the Almeria province, and are not only determined by their technical feasibility, but also by political decisions. While these can be extremely complex, and are outside the scope of this work, it is worth briefly discussing them.

Being barely the most widespread rainfed-grown crop in Almeria, it represents the most important alternative to greenhouse-based agriculture. Also, barley is grown in areas far from Almeria's coast, where greenhouse horticulture is practiced. Therefore, incentivizing the production of this crop could constitute a way of diversifying its economy while ensuring livelihoods in areas that might not be interested by the economic benefits linked to intensive horticulture. This last factor could also play an important role when it comes to avoiding migrations from the inland to the coast, ensuring rural development and less pressure on urban areas. In this context, the scenario might be to push for either an increase in size of the sown areas, or an increase in productivity (or both). Both options requiring much more water for irrigation, and weighing more on the province's water resources which, according to the Junta de Andalucia (2023), will be more and more reliant on desalination plants. Such desalinated water however will likely be allocated to greenhouses due to geographical reasons (the closeness to the coast). Barley cropping will instead likely still rely on natural water resources the management of which might be in the future limited due to political decisions.

In this context it seems adivsible to policy-makers and politicians to follow the indications proposed in the *Plan Andaluz De Accion Por El Clima* (Junta de Andalucía. Consejería de Agricultura Ganadería Pesca y Desarrollo Sostenible., 2021). Creating task forces and support systems for farmer to promote sustainable agricultural practices and conservative agriculture. This, to limit the climate change impact on agriculture and develop a more resilient agricultural system. It would be particularly crucial supporting farmers on the field, and co-developing adaptation strategies. This values local knowledge, engagning local communities and making the proposed climate change adaptation strategies stronger and more easily accepted on a local level.

The proposed scenario was not developed by any literature source and is one of the many different possible development pathways that the Almeria province might undertake. However, it helps in understanding the different factors that might affect decision-making processes related to adaptation, and therefore how the results proposed in this thesis might have different possible practical feedback.

The crucial thing to highlight is that the results show that adaptation is possible. However, it will come with a cost, here quantified in terms of water but that can also be translated into an economic cost, therefore requiring decisions on how to allocate resources. And such decisions are linked to the different paths of development that the province will take.

5.3 Limitations of the modeling approach and suggestions for future studies

The proposed research has various limitations that have been explicitly mentioned throughout the text to state the domain of applicability of the results obtained. Here these limitations are summarized, and suggestions for future works are put forward.

The most important limitation introduced is the use of the standard barley parametrization instead of a locally calibrated parametrization. Such barley dataset was indeed calibrated in

Ethiopia and has a life cycle that is shorter than the one reported in literature for the Almeria province (Subsecretaría de Agricultura & Pesca y Alimentación, 2014). This introduces uncertainties concerning the modeling of the crop's growth and the response of the crop to the climate in its different growing stages. This is particularly limiting for future projections because it does not allow to account for spring's changes in climate, which might affect the results. It is therefore suggested that future studies carry out a minimal calibration to account for local conditions and local barley varieties, for instance as done by Therond et al. (2011), who just roughly adjusted crucial parameters to enhance the results.

Moreover, the level of detail of the inputs provided was limited and represented an approximation and an average of the different conditions that characterize local agriculture. This can be improved in future studies, for instance by using climate data specific to the areas where barley is grown, rather than an average of the climate of the whole province. Here, applying a modeling approach based on pixels, as the one proposed by de Roos, et al. (2021), also including information on soil type and soil water content and running AquaCrop for each pixel, can improve the results. This approach can also allow to assess the spatial variability of the results.

Another significant limitation of the proposed study is the fact that the initial soil water content was unknown and that the model was unable to predict it through a continuous soil water balance, being this latter approach indicated by Steduto, et al. (2012) to cope with the absence of field data. The approach proposed in this work addressed this issue by identifying a reference initial soil water content, then used to create ISWC sub-scenarios to link to the main SSP scenarios, following the approach adopted by Cammarano, et al. (2019), and Al-Bakri, et al. (2011, 2021), for precipitation and temperature. This way of working, while allowing to assess the importance of the parameters that characterize each scenario, lacks the ability of giving strong indications for the future. Future studies should thus incorporate in the model either projections of soil water availability changes, or a soil water balance to estimate the soil water content at sowing.

While among the main strengths of the proposed approach is the fact that it requires a low number of inputs that are easily found online, it is lacking in all the fields where local knowledge is needed, such as field management practices. This information, or at least an indication, could be retrieved in future studies through confrontation with local stakeholders and then integrated into the modeling. This step, however, comes with an increased effort for precision, and needs to be coupled with improvements in all the other aspects that limit the precision of the proposed modeling approach, otherwise it would not be useful. Also, the process of interacting with local stakeholders might be very time and resource-consuming, thus, this further effort should be planned only in case increased precision is needed.

Lastly, in this work, adaptation options have been modeled to be the same through all the analyzed scenarios, not taking into account that the different SSP scenarios come with a linked narrative. Within each SSP some adaptation options are more likely than others, and in some scenarios barley cropping itself might not even be an option anymore. These considerations were not included in this work. However, future studies might want to develop adaptation scenarios coherent to the different narratives.

6. Conclusions

The proposed work aimed at evaluating the climate change impact and the performances of different climate change adaptation options on rainfed barley production in the province of Almeria, Spain. This analysis was carried out under three different SSP scenarios, SSP1-2.6, SSP2-4.5, and SSP5-8.5, and in two time periods, mid-century (2041-2070), and end-century (2071-2100). To achieve the proposed objectives, the FAO's AquaCrop model was used, in its Python implementation.

Because of the spatial scope of the analysis, and the overall aim to capture trends of change in 30-year time windows, the model was run with inputs that constituted an approximation of local conditions. The choice of running the model with the not locally calibrated, standard barley dataset already available in AquaCrop, was the most important approximation made, having all the studies found in the literature carried out a minimal calibration to account for local crop varieties. The absence of clear indications regarding the initial soil water content, coupled with the limitations of the selected AquaCrop implementation required the development of a procedure to estimate this parameter.

This work proposed an approach of solving this issue based on statistical analysis to identify the initial soil water content that better related, in terms of mean, correlation, and error, with the historical observed dataset for the years 1985 to 2014. The reference initial soil water content was then used as a baseline to develop three different sub-scenarios of initial soil water content, having acknowledged the importance of this parameter from the literature, and its possible decline due to climate change.

Overall, the proposed approach was found suitable to capture trends in rainfed barley growth in Almeria if the analyzed time window is of at least 10 years, and if an error of around 10% on the estimated mean is accepted.

Future projections were then run to evaluate the impacts of climate change, and to evaluate how three different adaptation strategies performed to mitigate these impacts: irrigation, the application of mulches, and the change in sowing date. All the results from this analysis were expressed in terms of percentual change from the average modeled yield of the baseline period.

The results obtained indicate an average yield change between +14% and -45% at mid-century, and between +12% and -55% at end-century, with significant criticalities linked to a 10% TAW initial soil water content, and SSP5-8.5. Also, they indicate increases in productivity under rainfed conditions in the case the initial soil water content stays constant in the future. These results are comparable with what was found by other studies and are highly dependent on the initial soil water scenario. Which was identified as the main parameter to be watched for predicting future yields and planning adaptation action.

Concerning the adaptation solutions, irrigation was found to be the one strategy that had the greatest impact on the results, resulting in possible increases of 20% to 10% in average yield if, respectively, over 300 m³/ha of water are supplied over the whole growing season in conditions were the initial soil water content is 10% TAW, and over 200 m³/ha under a 20% TAW initial soil water content. On the other hand, with a 30% TAW initial soil water content such increases happen even without the need for irrigation water. If the amount of seasonal irrigation water provided drops instead down to 5 or 10 m³/ha average yields are expected to decrease between -30% and -40% (mid-century), and -35% and -45% (end-century) with an initial soil water content of 10%. Indicating that the application of water might not always be optimal, and should be planned carefully, taking into consideration the limitations in water availability of the province. Overall, the work found that the ideal irrigation threshold for maintaining constant barley yields in the future might be found between 0% TAW and 20% TAW.

Mulches were found to be effective in mitigating both irrigation needs and water requirements, even if at low amounts in absolute terms. On the other hand, it was not possible to retrieve clear indications on the effectiveness of changing the sowing date in the future to adapt to climate change.

Overall, the study indicates that climate change adaptation for the barley cropping sector in the Almeria province is feasible. The results suggest that this should first aim at reducing loss in soil water content in the future to ensure optimal conditions for the crop’s growth, and only afterward undertake water-intensive adaptation pathways like irrigation to compensate for productivity losses. This, is to avoid as much as possible weighting on the already scarce water resources of the province.

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Appendix

Table 14A. *Difference between the average modelled yields in the management options and climatic scenarios.*

	2041-2070			**2071-2100**		
ISWC Scenario	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	-0,59	-0,67	-0,70	-0,72	-0,67	-0,87
20% TAW	-0,19	-0,20	-0,20	-0,24	-0,16	-0,43
30% TAW	0,18	0,22	0,17	0,10	0,19	0,06

Table 15A. *Average modelled yields under the different management options and climatic scenarios.*

	2041-2070			**2071-2100**		
ISWC Scenario	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	0,98	0,90	0,87	0,85	0,90	0,70
20% TAW	1,38	1,37	1,37	1,33	1,41	1,14
30% TAW	1,75	1,79	1,74	1,67	1,76	1,63

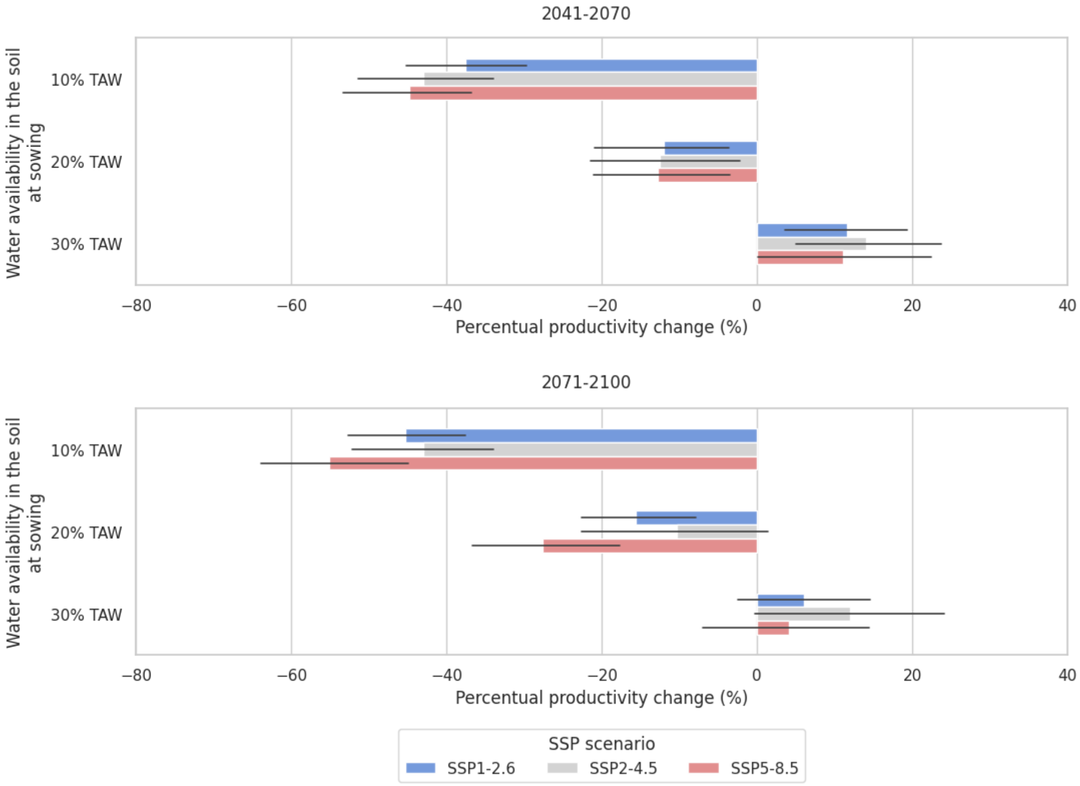

Figure 17A*. Visual representation of the climate change impact on rainfed barley under the analyzed SSP scenarios and time periods.*

***Table 16A**. Absolute change in yields under different management options and climatic scenarios. Irr. Thrsh. = Irrigation Threshold; M = Mulches*

ISWC Scenario	Management	2041-2070			2071-2100		
		SSP1-2.6	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	**No Irrigation**	**-0,59**	**-0,67**	**-0,70**	**-0,72**	**-0,67**	**-0,87**
	Irr. Thrsh. 0%	**-0,50**	**-0,59**	**-0,60**	**-0,63**	**-0,58**	**-0,70**
	Irr. Thrsh. 0% + M	**-0,46**	**-0,53**	**-0,55**	**-0,59**	**-0,55**	**-0,66**
	Irr. Thrsh. 20%	**0,28**	**0,33**	**0,32**	**0,19**	**0,33**	**0,32**
	Irr. Thrsh. 20% + M	**0,35**	**0,37**	**0,39**	**0,25**	**0,38**	**0,38**
20% TAW	**No Irrigation**	**-0,19**	**-0,20**	**-0,20**	**-0,24**	**-0,16**	**-0,43**
	Irr. Thrsh. 0%	**-0,19**	**-0,20**	**-0,20**	**-0,24**	**-0,16**	**-0,43**
	Irr. Thrsh. 0% + M	**-0,12**	**-0,12**	**-0,13**	**-0,18**	**-0,10**	**-0,34**
	Irr. Thrsh. 20%	**0,12**	**0,17**	**0,10**	**0,05**	**0,12**	**0,04**
	Irr. Thrsh. 20% + M	**0,21**	**0,24**	**0,21**	**0,13**	**0,22**	**0,14**
30% TAW	**No Irrigation**	**0,18**	**0,22**	**0,17**	**0,10**	**0,19**	**0,06**
	Irr. Thrsh. 0%	**0,18**	**0,22**	**0,17**	**0,10**	**0,19**	**0,06**
	Irr. Thrsh. 0% + M	**0,24**	**0,27**	**0,24**	**0,16**	**0,25**	**0,15**
	Irr. Thrsh. 20%	**0,19**	**0,22**	**0,18**	**0,11**	**0,20**	**0,09**
	Irr. Thrsh. 20% + M	**0,24**	**0,28**	**0,25**	**0,17**	**0,27**	**0,18**

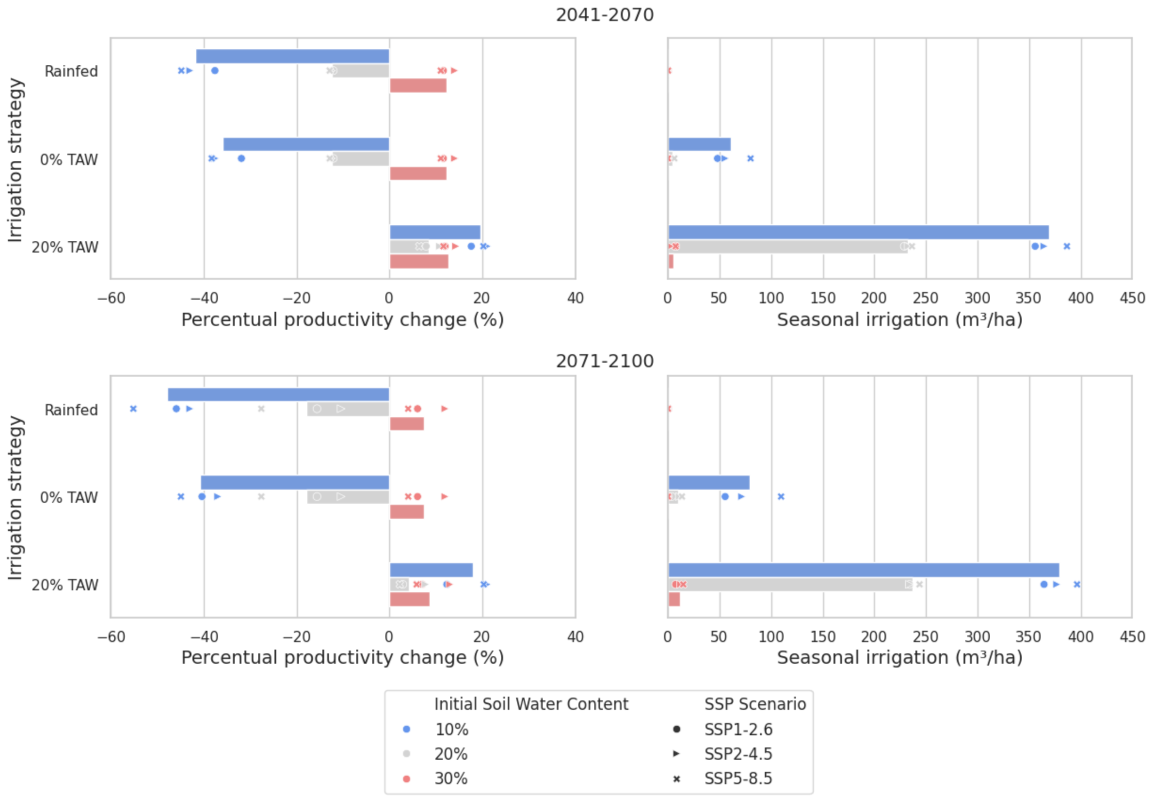

***Figure 18A.** Visual representation of the impact of irrigation on rainfed barley production and the respective irrigation needs under the analyzed SSP scenarios and time periods.*

***Table 17A**. Mulches performances (absolute impacts on irrigation needs and yields). Irr. Thrsh. = Irrigation Threshold; Y.I. = Yield Change; I.D.C. = Irrigation Demand Change.*

ISWC Scenario	Management	2041-2070			2071-2100		
		SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
10% TAW	**Irr. Thrsh 0% - Y.I.**	0,04	0,06	0,05	0,05	0,03	0,05
	Irr. Thrsh 0% - I.D.C.	-9,85	-4,93	-4,93	-7,39	-6,16	-12,32
	Irr. Thrsh 20% - Y.I.	0,07	0,04	0,07	0,05	0,05	0,06
	Irr. Thrsh 20% - I.D.C.	-11,08	-18,47	-16,01	-14,78	-16,01	-19,70
20% TAW	**Irr. Thrsh 0% - Y.I.**	0,07	0,08	0,07	0,06	0,06	0,09
	Irr. Thrsh 0% - I.D.C.	0,00	-1,23	-2,46	-1,23	-1,23	-2,46
	Irr. Thrsh 20% - Y.I.	0,08	0,07	0,11	0,08	0,09	0,10
	Irr. Thrsh 20% - I.D.C.	-2,46	-4,93	0,00	-3,69	-2,46	-3,69
30% TAW	**Irr. Thrsh 0% - Y.I.**	0,05	0,05	0,07	0,06	0,06	0,09
	Irr. Thrsh 0% - I.D.C.	0,00	0,00	0,00	0,00	0,00	0,00
	Irr. Thrsh 20% - Y.I.	0,05	0,05	0,07	0,06	0,06	0,09
	Irr. Thrsh 20% - I.D.C.	-1,23	0,00	0,00	-1,23	0,00	-1,23

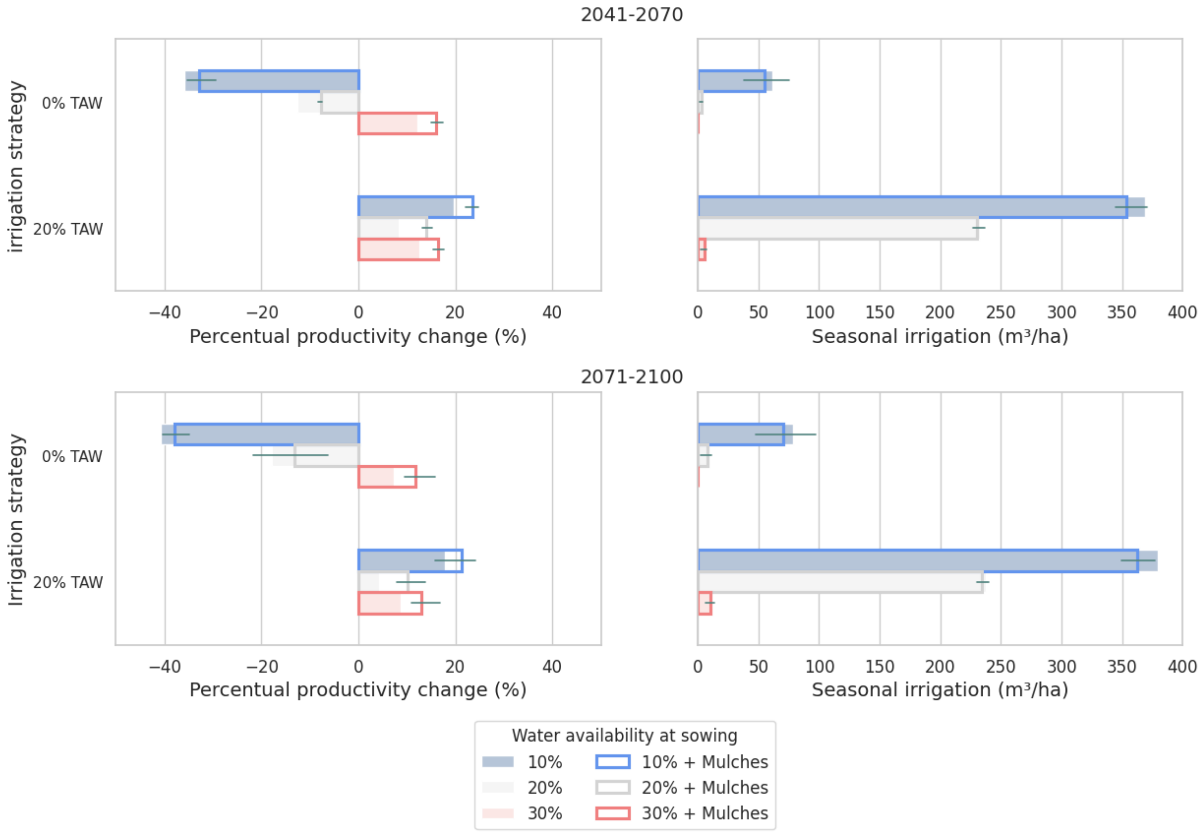

***Figure 19A**. Impact of mulches application on rainfed barely productivity under the analyzed time periods and SSP scenarios.*

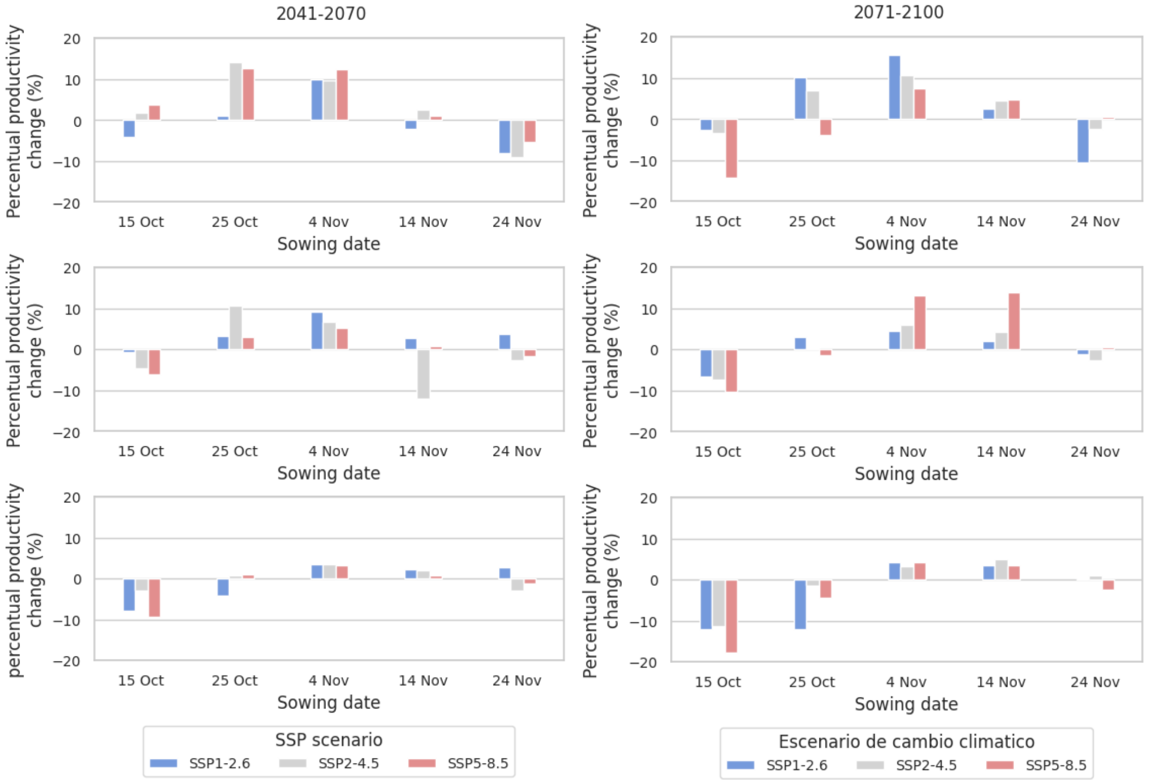

Figure 20A. *Impact of sowing date change on rainfed barley productivity compared the rainfed productivity for each scenario but with the sowing date on the 10th of November.*