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Impacts of Climate Change and Adaptation Strategies for Rainfed Barley Production in the Almería Province, Spain

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Abstract: Mediterranean water-stressed areas face significant challenges from higher temperatures and increasingly severe droughts. We assess the effect of climate change on rainfed barley production in the aridity-prone province of Almería, Spain, using the FAO AquaCrop model. We focus on rainfed barley growth by the mid-century (2041–2070) and end-century (2071–2100) time periods, using three Shared Socio-economic Pathway (SSP)-based scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5. Using the paired *t*-test, Spearman and Pearson correlation coefficient, Root Mean Squared Error, and relative Root Mean Squared Error, we verified AquaCrop's ability to capture local multi-year trends (9 or more years) using standard barley crop parameters, without local recalibration. Starting with a reference Initial Soil Water Content (ISWC), different soil water contents within barley rooting depth were modelled to account for decreases in soil water availability. We then evaluated the efficiency of different climate adaptation strategies: irrigation, mulching, and changing sowing dates. We show average yield changes of +14% to −44.8% (mid-century) and +12% to −55.1% (end-century), with ISWC being the main factor determining yields. Irrigation increases yields by 21.1%, utilizing just 3% of Almería's superficial water resources. Mulches improve irrigated yield performances by 6.9% while reducing irrigation needs by 40%. Changing sowing dates does not consistently improve yields. We demonstrate that regardless of the scenario used, climate adaptation of field barley production in Almería should prioritize limiting soil water loss by combining irrigation with mulching. This would enable farmers in Almería's northern communities to maintain their livelihoods, reducing the province's reliance on horticulture while continuing to contribute to food security goals.

Keywords: climate change adaptation; mediterranean; barley; Almería; irrigation; mulches; soil water content; AquaCrop model

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Citation: Saretto, F.; Roy, B.; Encarnação Coelho, R.; Reder, A.; Fedele, G.; Oakes, R.; Brandimarte, L.; Capela Lourenço, T. Impacts of Climate Change and Adaptation Strategies for Rainfed Barley Production in the Almería Province, Spain. *Atmosphere* **2024**, *15*, 606. https://doi.org/10.3390/atmos15050606

Academic Editors: Demetrios E. Tsesmelis and Nikolaos Skondras

Received: 31 March 2024
Revised: 3 May 2024
Accepted: 10 May 2024
Published: 16 May 2024

1. Introduction

The Mediterranean region is often identified as a climate change hotspot [1]. More intense warming and drying are projected in this area than in other parts of the world [2]. Even considering adaptation efforts, new climatic conditions will impact the countries and the communities of the Mediterranean region in a variety of ways, with different magnitudes and consequences [3]. It is widely accepted that agriculture will be one of the most affected sectors with projections of decreased yields, greater irrigation needs [3,4], and reduced water availability [5,6].

Barley is one of the most resilient crops to water and temperature stress [7–10]. Thanks to its deep rooting system, it can endure drought [8,10], and it is believed to adapt to stressful conditions better than other cereals [7,8]. Barley thrives under both cold and warm climates [10], and thanks to its relatively short growing season, it can be grown in areas with limited rainfall [9]. Thanks to its resilience, barley thrives in the Mediterranean basin, serving multiple purposes, including livestock feed, beer and other alcohol production, and human nutrition [9,10]. Barley can also be a crucial stage in crop rotation, with benefits related to pest and disease control [10].

Notwithstanding its resilience and endurance, barley production is expected to be impacted by climate change [11,12]. The foreseen alteration in temperature and precipitation patterns that will affect the Mediterranean, along with the increased probability of extreme events, will reduce yields and increase the risk of crop failure [3,10]. An increase in dry conditions has already been reported by the IPCC for the whole Mediterranean region (defined by the cited source as the area ranging from northern Italy to the north of Morocco and Tunisia, and from Spain to Lebanon), and the trend is projected to continue in future climate change scenarios, posing inevitable threats to water availability [3]. Under the projected drier and warmer environmental conditions, even this stress-resilient crop might face crop losses [10].

Several studies have investigated and tried to quantify the effects of climate change on barley production in the Mediterranean region. Bento et al. [12] found that under climate change, the production of barley and wheat will decrease in the southern region of the Iberian Peninsula, mainly due to an increase in spring maximum temperature. On the contrary, an increase in yields is projected in the northern parts of the Iberian Peninsula, with the main driver being early winter warming [12]. Cammarano et al. [11] focused on the whole Mediterranean basin and defined three scenarios of water availability: "dry", "mid", and "wet". By mid-century and under Representative Concentration Pathway (RCP) 4.5, the study projected a decrease in yields of 27% under the "dry" scenario and increases of 4% and 8% under the "mid" and "wet" scenarios. The authors stressed the importance of soil water content at the beginning of the growing season as a critical factor for barley growth [11]. This was supported by Al-Bakri et al. [13] when focusing on barley growth in Jordan. The same authors analysed three case studies representing semi-arid Mediterranean environments in Jordan (BSk in Köppen–Geiger classification [14]), considering RCP4.5 and RCP8.5 at both the mid-century (2030–2050) and end-century (2080–2100) time periods [15]. The results of their study indicate a decrease in barley yields between 5% and 30%, with an average decrease of 12% in grain yields and of 16% in biological yields due to drier environmental conditions [15].

Due to its suitability for water-stress conditions, the FAO AquaCrop model is often used to study barley growth; however, only a few cases exist focusing on the Mediterranean area. Dhoiub et al. [16] carried out a multicriteria analysis to evaluate barley growth in hilly agrosystems in Tunisia. Alaya et al. [17] adopted barley as one of the sample crops to evaluate the scalability of AquaCrop results through GIS. Both of these works utilize the same parametrization, which was developed for salinity stress and irrigated conditions by El Mokh et al. [18]. López-Urrea et al. [19] also provided a parametrization for barely in a Mediterranean setting, but it focuses on high-yielding barley.

When interested in the applications of AquaCrop for climate change impact assessment on barley, we have to move outside the Mediterranean. In a study on Northern Serbia, Daničić et al. [20] found that while the flowering time and the overall phenology of the crop changed, yields were largely unimpacted in the mid- and end-century time periods. Dubey and Sharma [21] focused on the basin of the Banas River in India and showed how in the mid-century (2021–2050) time period and under RCP4.5 yields were projected to increase. Yawson et al. [22–24] studied climate change's impact on barley production for malting beer and for food security in the UK. They suggest possible increases in yields if the effects of climate change alone are considered [23]. Lastly, Arce-Romero et al. [25]

applied the model to two Mexican case studies, projecting yield decreases in the future, smoothed if mulching or a change to later sowing dates was adopted.

All the aforementioned studies include, to differing extents, a calibration of the crop's parameters. Such calibration is generally conducted through field experiments [19–21,26], literature data [24,25], algorithms [27], or satellite imagery [28,29]. For experimental calibration, the process requires multiple years of data and agronomic knowledge, making the process resource- and time-intensive. After calibration, validation is required. This is normally conducted by comparing the results obtained in the model using the calibrated parameters and experimental data and through a set of statistical indicators such as Root Mean Squared Error, Index of Agreement, Nash–Sutcliffe efficiency, and Goodness of Fit [12,19,26,30].

The process of calibration enhances the accuracy of the results; however, as highlighted by Coudron et al. [31], these can still be affected by other uncertainties within the model, such as those linked to local climate variability. When considering the accuracy of the results, it is important to remember that AquaCrop was developed for field-scale modelling [32]. Therefore, it requires high-quality inputs to model inter-annual changes in productivity. However, such a focus on the crop parameters becomes less important in larger-scale applications of the model, as in the work by de Roos et al. [33].

Aim of the Study

Our study focuses on the Spanish province of Almería, an area of transition from a Mediterranean to a semi-arid climate. Almería is an interesting case study as it relies on the agricultural sector for its economy, particularly on greenhouse-based intensive horticulture which uses a large amount of water [34,35]. In Almería, barely is the main field crop, in most cases grown under rainfed conditions and mainly planted in northern areas of the province, in which greenhouse intensive agriculture is not present [36]. Due to Almería's situation in southern Spain, climate change threatens to make barley cropping no longer a source of livelihoods for local farmers [12]. To improve the understanding of the impact of climate change on agriculture in a semi-arid area as Almería, and provide tools for developing adaptation strategies, the work is guided by two central research questions:

1. How and to what extent will barley production change in the mid- and end-century time periods under different climate change scenarios in terms of multi-year trends?
2. What is the efficacy of irrigation, mulching, and changing the sowing date as adaptation strategies to address the effects of climate change in the province?

Research question 1 will provide knowledge on future trends in barley production at the provincial scale, allowing for more readily available information for local stakeholders to drive climate action. Research question 2 will provide insights on the efficacy of climate change adaptation practices that have been suggested by practitioners in the region [37], giving a more profound understanding of possibilities to adapt barley production to climate change. It should be noted that the impact of climate change on rainfed barley production in this study is intended solely in terms of overall yields, and the agronomic aspects explaining these are beyond the scope of the current paper.

We applied the FAO AquaCrop model [32] in its Python implementation—AquaCrop-OSPy [38]—at the scale of Almería province and for two 30-year time horizons, mid-century (2041–2070) and end-century (2071–2100), comparing them with a baseline period (1985–2014). For each time period, three Coupled Model Intercomparison Project phase 6 (CMIP6) Tier 1 Shared Socioeconomic Pathway (SSP)-based scenarios [39] were analysed: SSP1-2.6, SSP2-4.5, and SSP5-8.5. To account for possible losses in soil water availability at the beginning of the growing season, three levels of Initial Soil Water Content (ISWC) were considered: 30% of the Total Available Water (TAW), 20% TAW, and 10% TAW.

The focus on multi-year trends, the limits of Mediterranean parametrizations for barley [18,19], and the time and resource requirements for crop calibration led to the development of a framework where AquaCrop was run with the standard barley crop parameters available in Aqua-Crop-OSPy (based on an Ethiopian case study), without local recalibration. To evaluate the applicability of the proposed approach, the model's results from the baseline period were compared through a statistical analysis with a historically observed dataset of barley yields for the target province from the Spanish Ministry of Agriculture. This allowed us to retrieve a reference ISWC and the minimum number of years needed to be studied together to retrieve meaningful information on barley yield trends.

The results obtained in this work can be used by local stakeholders and policymakers to develop long-term strategies for climate change adaptation. The overall simulation framework can constitute an example to be followed in other regions, to obtain preliminary indications of crop yield changes. Having acknowledged the lack of studies applying AquaCrop to study climate change impact on barley in the Mediterranean region, this study also suggests the possibility of extending the use of this model with such purpose in this area.

2. Materials and Methods

2.1. Case Study Overview

Almería is a southern Spanish province located in the Mediterranean (Figure 1). The province occupies an area of 8775 km^2 [40] and has a population of 730,430 inhabitants [41]. Almería is known for its aridity, with an average yearly precipitation of 300 mm and an average maximum temperature of 18 °C [34]. The province has a predominantly cold semi-arid (steppe) climate (BSk, in the Köppen–Geiger classification), with coastal areas of a hot semi-arid (steppe) climate (BWh) and some inland areas of a hot-summer Mediterranean climate (Csa) that border the more mountainous areas of a warm-summer Mediterranean climate (Csb) [34,42].

The Almerían economy is highly reliant on agriculture, with greenhouse horticulture as a dominant sub-sector, accounting for 31,614 hectares of land coverage [43]. These greenhouses produce over three million tons of fruit and vegetables per year, much of which is exported to the rest of Europe [44]. The size and intensive nature of the horticulture sector has severe implications for water resources, with irrigation activities in the greenhouse sector relying on the extraction of groundwater, which, in turn, has led to the shrinking of the groundwater table and deteriorating water quality [3,43]. Overall, the greenhouse-based agriculture system in the region causes non-negligible sustainability issues [35,45]. Climate change is expected to exacerbate these challenges by reducing precipitation and intensifying drought in the already water-stressed areas of this region, which will impact the whole agricultural system [3].

The most important field grown crop in Almería province is barley [36]. In 2018, this crop occupied roughly 8500 hectares, of which more than 8100 were classified as rainfed [36]. Most of the barley fields are in the north-northwest of the province (Figure 1) and barley is sown in winter (October to December) and harvested in late spring (May to June) [46].

Studying the role of barley in the context of water (over)use for horticulture has local relevance because of its importance in the north of the province where the economic benefits of greenhouse agriculture are not as significant as in coastal areas but also because of the need for an improved understanding of its future role in the agricultural sector of the Mediterranean, a hotspot for climate change.

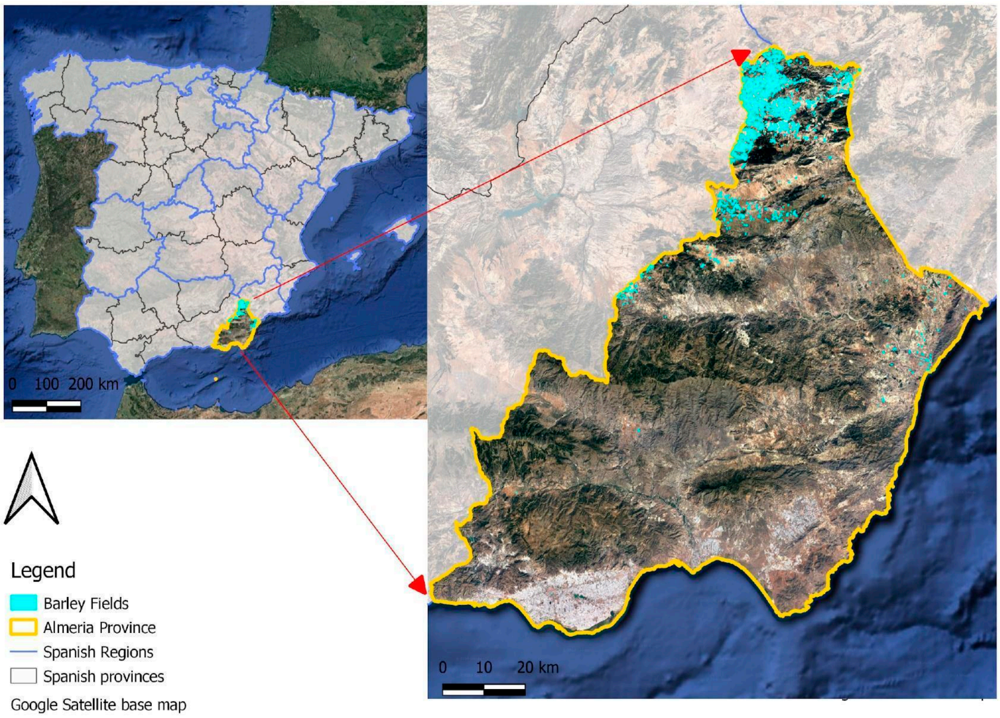

Figure 1. Map of the Almería province in Spain, with identification of rainfed barley fields (source: own elaboration based on Google satellite imagery and data from d'Andrimont et al. [47]; Figure S1 in the Supplementary Material shows an aerial picture of Almería's landscape.

2.2. Crop Simulation

The AquaCrop model in its Python implementation (AquaCrop-OSPy) was chosen due to its suitability for conditions where water stress is salient and due to its applicability for climate change risk assessment on crops [32]. AquaCrop's suitability for studying barley growth in Mediterranean environments has been demonstrated [16–18]. It has been shown to be adaptable to the needs of end-users outside of crop modellers and scientists (i.e., consultants and farmers) [48], and its better performance compared to other crop models in simulating barley yields in Mediterranean case studies has been verified [49,50].

AquaCrop-OSPy preserves the core functioning of the original model [38]. AquaCrop-OSPy version 2.2.3 [38] was used in this study, the latest model version available at the time. It requires four main categories of data as inputs: climate, crop, soil, and field management options [32]. The minimum input requirements for AquaCrop-OSPy are summarised in Table 1. These inputs are critical for crop modelling, as they are required to obtain a baseline crop dataset, among other features.

Table 1. Minimum input requirements for AquaCrop-OSPy [32].

Climate Data	Soil Data	Crop Characteristics	Management Practices
Minimum temperature	Soil texture	Crop type and parameters	Soil fertility level
Maximum temperature	Soil depth	Calendar type	Weed infestations
Potential evapotranspiration	Groundwater table	Sowing date	Practices that affect soil–water balance
Rainfall	Initial Soil Water Content		Irrigation strategy
CO_2 concentrations			

AquaCrop-OSPy has some known limitations. For example, version 2.2.3 lacks the possibility of implementing a continuous soil–water balance. This option would allow for modelling fluctuations in water availability in the soil and providing a realistic estimation of the soil water content at sowing, which is a critical parameter in AquaCrop.

Workarounds were used to overcome this issue and are explained in Section 2.3.1.

2.2.1. Climate Data

Daily climate variables for Almería province were obtained by statistically downscaling a set of Global Climate Models from their coarse spatial resolution to a fine grid. For each climate variable, the climate information was interpolated from the "native" resolution of the coarse grid to the "reference" resolution of the fine grid. Subsequently, point-by-point statistical relationships were established between raw "interpolated" and "reference" time series during training, considering each month separately to maintain the seasonality of climate information. These relationships were retrieved using the Empirical Quantile Mapping approach [51,52]. Finally, the same statistical relationships established during training between coarse and fine climate information were adopted to derive high-resolution climate information in the prediction period. In this way, it was possible to downscale the GCM-CMIP6 climate projections (i.e., coarse-resolution model) to a target grid of 5.5 km $\times$ 5.5 km, adopting the CERRA climate reanalysis [53] as the fine-resolution training model. The data from eight CMIP6 models were used: ACCESS-CM2, CESM2, CNRM-ESM2-1, EC-Earth3-Veg-LR, HadGEM3-GC32-LL, IPSL-CM6A-LR, MIROC4, and Nor-ESM2-MM. The climate variables were provided for three different timelines, 1985–2014 (baseline period), 2041–2070 (mid-century), and 2071–2100 (end-century), and three distinct climate change scenarios, SSP1-2.6, SSP2-4.5, and SSP5-8.5. The standard CO_2 concentrations available in AquaCrop-OSPy were used for the baseline period modelling and the scenario projections. These data are specific for each analysed SSP and represent different socio-economic development paradigms as well as different levels of atmospheric greenhouse gas concentrations [54].

2.2.2. Soil Data

Topsoil texture data were retrieved from the European dataset Topsoil physical properties of Europe (based on LUCAS topsoil data) [55]. A raster dataset with a resolution of 500 m provided information on the USDA soil textural class. This dataset was coupled with the European Soil Database of 2001 [56] to confirm that the soil did not have textural changes until a depth of 120 cm in the majority of Almería's rainfed fields. This verification allowed us to consider the topsoil data as a good approximation of the soil type.

The layer Topsoil physical properties of Europe (based on LUCAS topsoil data) [55] was then clipped in QGIS 3.28.2 [57] with the layer of barley fields in the province identified through EUCROPMAP 2018 [47]. This process indicated the *Loam* textural class as the most suitable to be selected for AquaCrop-OSPy modelling.

To consider possible changes in areas used for growing barley throughout the years, layer topsoil data were cross-checked using the CORINE Land Cover Dataset by selecting the *Non-irrigated arable land* areas from the 2006, 2012, and 2018 datasets [58–60], considering that barley is the largest non-irrigated crop in Almería province.

The soil depth was kept as default in AquaCrop-OSPy, at 1.2 m, divided into 12 layers of 0.1 m. In AquaCrop-OSPy, the bottom layer of the soil is programmed to expand if the rooting depth of the plant exceeds the soil depth [38]. The standard groundwater table as set by default in AquaCrop-OSPy was considered since no specific information about shallow groundwater resources in the area was found.

2.2.3. Historical Observed Yield Dataset

A dataset with historically observed rainfed barley yields in the Almería province was created by manually retrieving the values from the Spanish Ministry of Agriculture yearbooks on cereal production [61].

2.2.4. Crop Characteristics and Calendar Type

The barley crop parameters selected were the standard available in AquaCrop-OSPy's barley database [62]. No local calibration was performed. Standard AquaCrop-OSPy barley parameters are calibrated for a short cycle variety in the Tigray region in Ethiopia [62]. This region is mainly characterized by a Bsh (hot semi-arid) and a Bsk (cold semi-arid) climate [63], the latter being predominant in Almería [34,42]. This similarity in climates suggested the possibility of utilizing the standard parametrization for Almería. However, because of the short cycle of the barley variety, the growing season was modelled to be shorter than what is reported in the literature for Almería province, with the harvesting date in mid-February rather than in June [46]. This assumption introduces uncertainties in the results; however, it was accepted as a conservative approach to modelling since, being sown in November, the crop's growth happens in the wettest months of the year, thus reducing the water stress on the crop. This assumption is moreover coherent with the intent of the study of evaluating the possibility of retrieving meaningful information from AquaCrop-OSPy without fine-tuned input parameters. To assess the validity of this assumption, the results from the baseline period were tested as explained in Section 2.3.1.

AquaCrop-OSPy allows for the selection of two different barley parameterizations, one following calendar days and another following Growing Degree Days (°C day) [54]. The latter option was chosen, since it allows to users to analyse the effects of the thermal regime changes on the crop, making it more suitable for the assessment of climate change impact [32].

Sowing dates for barley in Almería range between mid-October and mid-December [46]. To find a suitable default sowing date for all simulated years, different model runs were programmed with sowing dates between the 15th of October and the 15th of December and compared to the historical observed dataset described in Section 2.2.3. The aim was to assess how sensitive the final yields were to this parameter and find which sowing date produced data most similar to the observed ones. Additionally, to evaluate the model's response to different sowing dates under different water stress conditions, two ISWC values were used, a low ISWC of 20% TAW and a high ISWC of 100% TAW. The results of this analysis are shown in Figure 2.

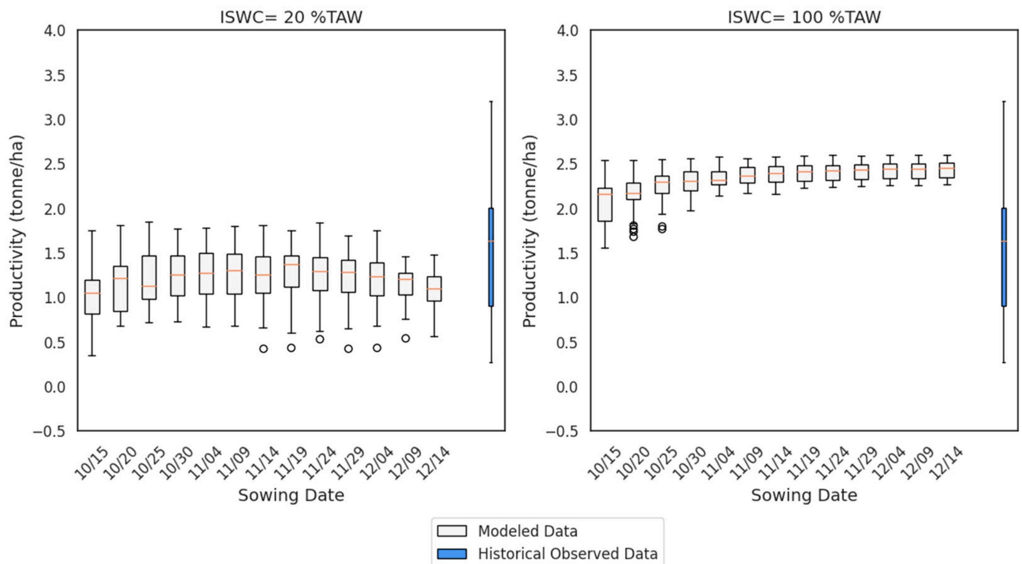

Figure 2. Sensitivity of AquaCrop-OSPy barley productivity results to the sowing date (MM/DD). Results obtained with an ISWC of 20% TAW (**left**) and 100% TAW (**right**). Each box represents the middle 50% of the values within each resulting dataset, the orange line indicates the median, and the circles indicate the outliers.

The results obtained with different sowing dates under the two ISWC parameterizations show a minimal difference. The 10th of November was selected as the reference sowing date, since it falls in the mid-range of the possible sowing dates that more closely match observed yields in the case of 20% TAW as ISWC.

2.2.5. Management Practices

The soil fertility level was set to 70% [33]. This value was determined using a crop recalibration for fertility stress as described in the Graphical User Interface (GUI) implementation of AquaCrop [54]. The modified crop parameters are presented in Table 2.

Table 2. Modified crop parameters considered in AquaCrop, to account for limited soil fertility. CCx = maximum canopy cover (fraction of soil cover); WP = water productivity normalized for ET0 and CO_2 (g/m^2); CDC = canopy decline coefficient (fraction per GDD/calendar day); CGC = canopy growth coefficient (fraction per GDD) [54].

Parameter	Default	70% Soil Fertility Level
CCx	0.80	0.48
WP	15.0	14.9
CDC	0.0060	0.0001
CGC	0.0087	0.0083

From the minimum input requirements of AquaCrop-OSPy, weed infestation and the application of mulches were excluded from the modelling, since capturing their yearly variability requires a level of information that is presently unavailable.

Mulches were not considered for the baseline period and were only modelled as an adaptation option in scenario projections, as explained in Section 2.3.2. The irrigation strategy was set to *Rainfed*. However, in the scenario projections, irrigation was modelled as an adaptation measure.

2.3. AquaCrop-OSPy Runs

2.3.1. Estimation of a Reference Initial Soil Water Content and Definition of the Model Domain of Applicability and Baseline Period

The approach used to estimate the reference ISWC was based on running the model for the baseline period (1985–2014) with different values of ISWC and comparing them with a historical observed dataset of rainfed barley yields in Almería (Section 2.2.3) for the same period using a set of statistical analyses.

These included the following: (1) a paired *t*-test with a significance threshold of 0.05; (2) a correlation analysis using the Pearson and Spearman correlation coefficients; and (3) an error analysis using the Root Mean Squared Error (RMSE) and relative Root Mean Squared Error (rRMSE), between the modelled and the observed distributions.

These analyses were carried out with a rolling average window approach to evaluate the minimum period needed in order for the resulting data to be considered meaningful. This consisted of an iterative approach, increasing the rolling average window applied to the datasets studied by 1 year for each iteration.

This process resulted in the selection of a reference ISWC, which acted as a benchmark for further analyses of possible decreases in soil water availability.

AquaCrop-OSPy was run for the baseline period (1985–2014) to retrieve a reference dataset of yields for comparison with future projections. This dataset resulted in yield projections for 29 years, rather than the typical 30 associated with climate risk assessments, due to the sowing date being set to the 10th of November, causing the first harvesting year to be 1986.

2.3.2. Future Scenarios and Projections

The AquaCrop-OSPy model was run under four different configurations, including one standard run to assess the impacts of climate change on rainfed barley; and three runs using different types of adaptation options: irrigation, mulches, and changes in sowing date. Adaptation strategies were modelled to be the same across all future climate change scenarios, notwithstanding the different narrative of socio-economic development within each SSP scenario [64]. Although this approach can be criticized from a purely scenario development perspective, it assures the coherence and comparability of the model across pathways (i.e., crop calibration or improved field management). Given the scale of the analysis, a significant change to model parameterizations of each adaptation option would add additional uncertainties to the modelling framework (e.g., fine-scale differences on how irrigation or mulching will occur under different SSPs) that outweigh the potential gain in model accuracy.

The standard run aimed to assess the impacts of climate change on rainfed barley, without considering any type of adaptation. To account for possible decreases in ISWC, three TAW parameterizations (30%, 20%, and 10%) were defined for each analysed SSP scenario and time horizon.

The use of irrigation as an adaptation strategy was included to evaluate its adaptation potential. It was implemented by setting the option *IrrMethod* to 1 and selecting the Soil Moisture Thresholds (SMTs), expressed in terms of percentage of TAW, which triggered irrigation for each life stage (emergence, canopy growth, max canopy, and senescence)**.** We focused on changing the SMT only for the emergence stage, as that is when the plant is more water-efficient. For this stage, the SMT was set to 0% TAW, and then to 20% TAW, simulating different scenarios of irrigation water availability. In both cases, for the other life stages, SMTs were kept at 0% TAW, the minimum value selectable within AquaCrop-OSPy for SMT values. A threshold of 0% TAW means that water is provided to the plant every time it goes below the Permanent Wilting Point (PWP). While this type of irrigation scheduling might not exactly mirror the decision-making processes of farmers, it was deemed a sufficient estimation of the irrigation water requirements in the province.

The modelling of the adaptation potential of mulching was conducted using the simulation framework defined in the previous section. Mulches were coupled with irrigation: their effect was therefore studied in terms of their contribution to improving the irrigation system. This is because of the limited water availability in the area, making the optimization of water use crucial. Mulches' presence was modelled in AquaCrop-OSPy, by setting the parameter *Mulches* to *True* and indicating that 100% (parameter *MulchPc*t = 100) of the soil was covered with mulches. This led to assessing their maximum potential impact on the results. Within AquaCrop-OSPy, mulches are considered only as a parameter reflecting their effect in reducing evapotranspiration from the soil [32]. In this study, organic mulches were modelled as suggested in the literature for the region [37]. This typology of mulches in AquaCrop-OSPy reduces soil evapotranspiration by 50% [54].

The change in sowing date served to estimate the adaptation potential of changing planting dates in barley production, without the presence of either irrigation or mulches; that is, using the same model framework but for rainfed conditions only. Multiple sowing dates were selected for analysis, spanning from the 15th of October to the end of November, with intervals of 10 days. The same model developed for the previous steps was routinely run changing the *PlantingDate* parameter to each sowing date. This range of dates is within the span reported by governmental authorities as being typical for barley sowing in Almeria [41]. The 10-day interval between sowing dates was defined for computational purposes, as the aim was to identify trends rather than specific "ideal" sowing dates, which reduces the unusefulness of analysing multiple, shorter, intervals.

3. Results

3.1. Climate Change Projections for Almería Province

Climate change projections for the province of Almería indicate a warmer and drier future. Minimum and maximum temperatures, along with potential evapotranspiration, are projected to increase while precipitation gradually decreases over time (Figure 3). The SSPs exhibit different trends, with SSP5-8.5 projecting the largest rate of change concerning the baseline period (1985–2014), for all four variables. Under this scenario, the increase in yearly minimum temperature can reach over 60%, with yearly maximum temperature and potential evapotranspiration increasing by 40% and 25%, respectively, by the end of the century. Under SSP5-8.5, precipitation is projected to decrease by 20% (mid-century) and 40% (end-century) when compared to the baseline period, while SSPs 1-2.6 and 2-4.5 show more moderate decreases, reaching 10% and 20%, respectively, by the end of the century.

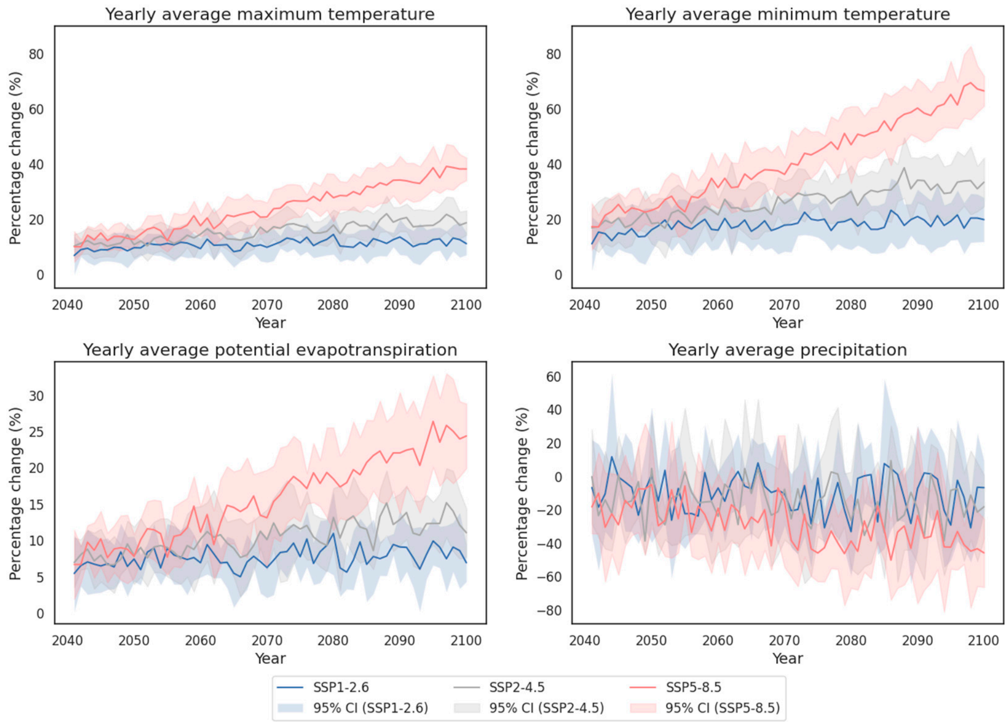

Figure 3. Projected change in the main climatic variables for Almería province, calculated as the percentage change from the average of the baseline period (1985–2014), for SSPs 1-2.6, 2-4.5, and 5-8.5. Precipitation (**top left**), evapotranspiration (**top right**), minimum temperature (**bottom left**), maximum temperature (**bottom right**); CI = Confidence Interval.

Water Availability

Water availability trends in Almería province were quantified by calculating the yearly difference between precipitation and potential evapotranspiration, expressed as the percentage change from the mean of the baseline period (1985–2014) (Figure 4).

Since precipitation will not mirror the increase in potential evapotranspiration (Figure 3), water availability is expected to continue to decrease in the region until the end of the century in all three analysed scenarios. However, there are differences in the changing trend between scenarios, in line with their different expected climate forcings.

Under SSP5-8.5, there is the greatest decrease in water availability. The difference between precipitation and potential evapotranspiration reaches an average of −60% of the baseline period by the end of the century, with a more pronounced decrease in precipitation and increase in potential evapotranspiration after the 2060s.

Water availability decreases at a lower rate in SSP1-2.6 and SSP2-4.5, with the results showing a constant trend with a decrease between −10% and −30% of the baseline period average.

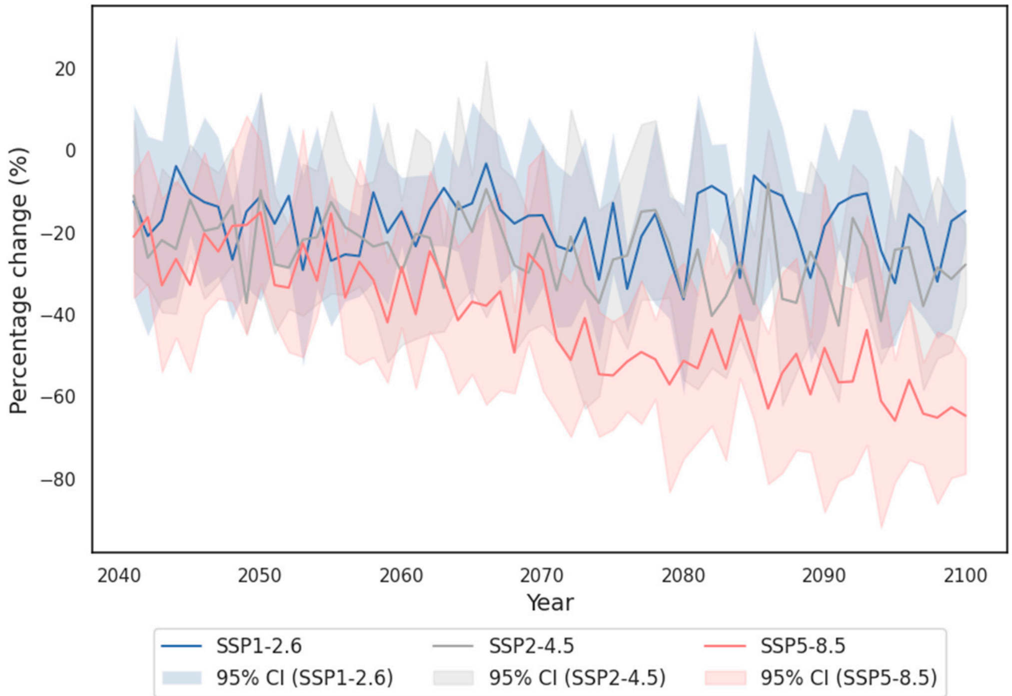

Figure 4. Projected difference between precipitation and potential evapotranspiration in Almería province, calculated as the percentage change from the average of the baseline period (1985–2014); CI = Confidence Interval.

The uncertainty range in the model's ensemble for scenarios SSP1-2.6 and SSP2-4.5 shows the possibility that water availability in Almería may remain equal, or even increase relative to the baseline period. However, and with the notable exception of the period up to 2060, this is not the case with SSP5-8.5, which shows a clear drying trend over the entire period.

3.2. Selection of the Reference Initial Soil Water Content (ISWC)

The modelling of barley production in AquaCrop requires inputting a reference value of Initial Soil Water Content (ISWC) in the form of the percentage of Total Available Water (TAW) in the soil. A statistical-based approach was used to better validate and match data with the real situation in the field without having to undergo field data campaigns. AquaCrop was run for the baseline period (1985–2014) with different values of ISWC, which were then compared to observed historical data of rainfed barley yields using a set of statistical analyses (paired *t*-test, Spearman and Pearson correlation coefficients, and error analysis). The results of this analysis are described in the following sections.

3.2.1. Paired T-Test

The AquaCrop-OSPy modelled yield distributions with the least significant mean difference to the historical observed dataset were obtained with 20% and 30% TAW (Table 3 and Figure S2 display instead the yield distributions obtained with the different ISWC values). Although modelled results using a TAW of 40% show a *p*-value of less than 0.05 (and thus the mean difference between modelled and observed paired samples may be significantly different from 0), the results were notably higher than for all other remaining TAW values (Table 3). For this reason, a TAW of 40% was also included as a model parameterization in our analysis.

Table 3. Average yields, standard deviation, and *p*-values of Student's paired *t*-tests between modelled runs using different TAW values and the historical observed dataset. The significance threshold was at 0.05, and the ISWC values considered for further analysis are reported in bold.

Initial Soil Water Content (%TAW)	Average Yield (tonne/ha)	Standard Deviation	*p*-Value
0	0.77	0.33	0.000015
10	0.85	0.31	0.000081
20	**1.27**	**0.32**	**0.090279**
30	**1.57**	**0.27**	**0.820800**
40	**1.87**	**0.24**	**0.032492**
50	2.29	0.12	0.000014
60	2.34	0.11	0.000005
70	2.35	0.11	0.000004
80	2.36	0.11	0.000003
90	2.36	0.11	0.000003
100	2.36	0.11	0.000004

3.2.2. Pearson and Spearman Correlation Coefficients

The relationships between the historical observed yield dataset and the modelled yield datasets for the baseline time period under all selected TAW levels (20%, 30%, and 40%) were analysed using Pearson and Spearman correlation coefficients. Statistical correlations were computed for multiple rolling average windows of yield datasets and the results are depicted in Figure 5.

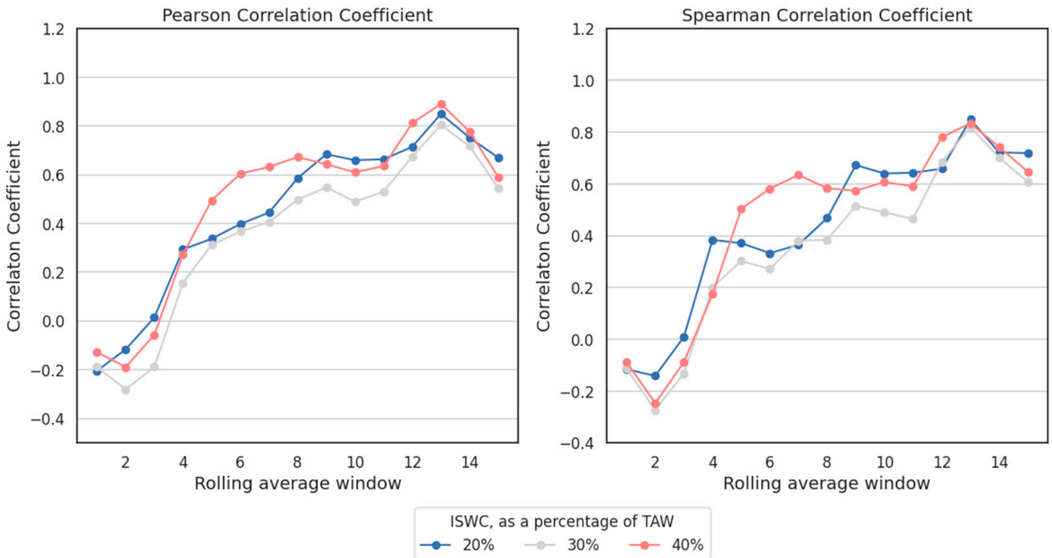

Figure 5. Pearson (**left**) and Spearman (**right**) correlation coefficients with varying rolling average windows between modelled yield data and historical observed data, for the 1985–2014 period.

Results show that, under all TAW levels, both correlation coefficients increase with an increasing rolling average window, reaching a maximum with a 13-year rolling average. Additionally, there are no significant differences between TAW levels in either coefficient, with correlation coefficients exceeding 0.6 observed above the 10-year rolling average windows.

The statistical significance of results for each rolling average window and TAW level (20%, 30%, and 40%) were evaluated for both correlation coefficients, using a *t*-test with a threshold of 0.05. In both correlation coefficients, statistical significance was verified for rolling average windows above 9 years, independently of the TAW level. Detailed results of this analysis are presented in Table S1.

3.2.3. Error Analysis

We used Root Mean Squared Error (RMSE) and relative Root Mean Squared Error (rRMSE) to analyse predicted error levels in modelled yield datasets, accounting for the three TAW levels studied. The results show that both RMSE and rRMSE become lower with an increasing rolling average window (Figure 6). The results include a steep decrease in both RMSE and rRMSE between 0 and 5 years of the rolling average window. Values reach low levels after that, namely below 0.4 of RMSE and 30 of rRMSE. Different error behaviours can be described depending on TAW levels, with a 30% TAW distribution reducing the error at a greater pace with the average window (going below 0.2 and 10 after the 10-year rolling average), and the curves of 20% TAW and 40% TAW plateauing at around 0.3 and 20 for each coefficient.

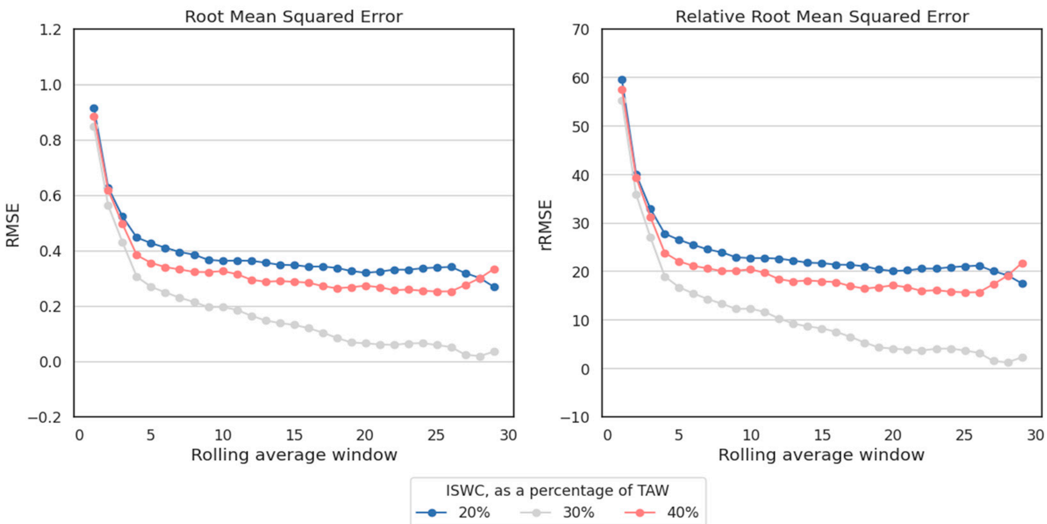

Figure 6. Root Mean Squared Error (**left**) and relative Root Mean Squared Error (**right**) between modelled and historical observed data for the 1985–2014 period, calculated for different rolling average windows.

Based on these results, a value of 30% TAW was selected as the reference ISWC for the model parameterization of the baseline period. This value leads to a reduction in errors while maintaining a good correlation and a good similarity with the historical observed dataset. This finding means that the analysis of future scenarios of decreases in water availability and adaptation options will be based on a comparison with the 30% TAW threshold, considered as the current condition.

3.3. Climate Change Impact on Rainfed Barley Yields

Climate change impacts on rainfed barley yields as percentage changes in yield are presented in Figure 7 for three climate scenarios (SSPs 1-2.6, 2-4.5, and 5-8.5) and three ISWC parameterizations (TAW of 30%, 20%, and 10%), by the mid- and end-century time periods.

The results indicate a decrease in yields for all the analysed cases, except for scenarios where 30% TAW is sustained, or, in other words, where the current ISWC at the sowing date is maintained. Even in this case, model uncertainty points toward the possibility of a potential loss of yield, with model results spreading to negative values in all three climate scenarios, and for both time horizons.

The largest changes in average yield reach −55.1% for a 10% TAW level at the end of the century in SSP5-8.5. For this TAW level, the minimum change observed is −37.6% at the mid-century period for SSP1-2.6.

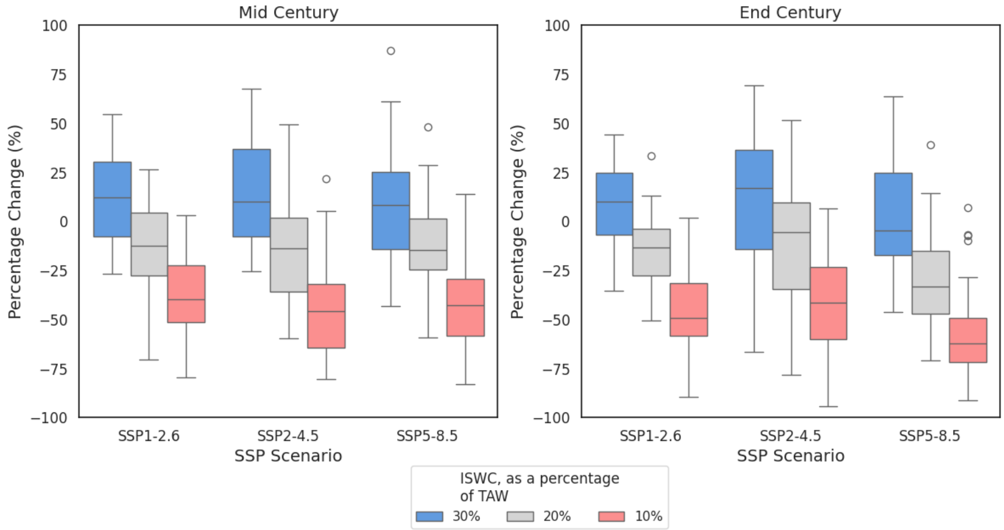

Figure 7. Percentage change (%) in rainfed barley yield for different Initial Soil Water Contents, in the mid-century (**left**) and end-century (**right**) time periods, under SSP1-2.6, SSP2-4.5, and SSP5-8.5. Box-plots refer to the median, quartiles, and 95% of distribution, the circles indicate the outliers.

In scenarios where the ISWC is maintained at the current level of 30% TAW, results range from an average yield increase of 14% under SSP2-4.5 at the mid-century period to a 4% increase under SSP5-8.5, for the end-century period.

Table S2 provides in-depth details on the average yield changes for each timeline and climate change scenario analysed.

In general, the ISWC parameterization affects barley yield more than climate change scenarios over both time horizons. For example, in the mid-century period, the results show minimal changes in yield for the same ISWC across climate scenarios. Nonetheless, there were significant changes for different ISWCs within the same climate scenario. This tendency remains at the end of the century, although the magnitude of change between ISWC parametrizations increases substantially compared to the previous period.

3.4. Climate Adaptation Pathways Analysis

3.4.1. Irrigation

To evaluate the climate adaptation potential of barley irrigation in Almería, each combination of climate scenarios and ISWC parameters was modelled in AquaCrop-OSPy using three different irrigation parameterizations: (a) absence of irrigation (rainfed); (b) irrigation triggered when soil water content drops below 20%; and (c) irrigation triggered when soil water content reaches 0% TAW (Table 4).

As for barley productivity impacts, ISWC parameterization influences irrigation needs more than climate scenarios. More water available at the beginning of the growing season means lower irrigation needs regardless of the climate scenario and time horizon.

Additionally, the choice of the irrigation threshold has different impacts according to the ISWC parameterization. For example, at the 10% and 20% ISWC levels, a TAW irrigation threshold set at 0% is not useful to avoid productivity losses. However, for the same ISWC levels, a 20% TAW irrigation threshold always increases productivity, across all scenarios and time horizons.

Table 4. Irrigation effect on barley production, expressed as percentage yield change (%) from the average of the baseline period, under SSP1-2.6, SSP2-4.5, and SSP5-8.5, for the mid- and end-century periods. Irrigation is triggered when TAW drops below 20% TAW or 0% TAW. Green cells indicate positive changes; red cells indicate negative changes. The intensity of the colour is proportional to how positive or how negative that change is.

		2041–2070			2071–2100		
ISWC	**Irrigation Threshold**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	No Irrigation	−37.6	−43.0	−44.8	−45.9	−43.0	−55.1
	0%	−31.9	−37.5	−38.3	−40.4	−37.0	−44.9
	20%	17.6	21.1	20.2	12.4	21.0	20.3
20% TAW	No Irrigation	−12.1	−12.5	−12.9	−15.6	−10.4	−27.6
	0%	−12.1	−12.5	−12.9	−15.6	−10.4	−27.6
	20%	7.9	10.8	6.4	2.9	7.8	2.2
30% TAW	No Irrigation	11.6	14.0	11.1	6.1	12.0	4.0
	0%	11.6	14.0	11.1	6.1	12.0	4.0
	20%	12.0	14.3	11.6	7.1	13.0	5.9

Another example of the importance of ISWC is the use of a 20% TAW irrigation threshold across scenarios. Somewhat contra-intuitively, this threshold yields better productivity results in the 10% ISWC than in the 20% and 30% ISWC scenarios, for all climate scenarios and time horizons. The reason for such an effect is that a lower soil water content at the beginning of the growing season causes the soil TAW to drop below the defined threshold more often, thus triggering more (and earlier) irrigation events in the model, leading to an increase in productivity.

The additional water requirements for barley irrigation in Almería linked to the results of Table 4 are presented in Table 5.

Table 5. Water requirements for the irrigation of barley in Almería, under irrigation thresholds set at 20% or 0% TAW for SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios and mid- and end-century horizons. Results expressed in m^3/ha for the whole growing season.

		2041–2070			2071–2100		
ISWC	**Irrigation Threshold**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	No Irrigation	0	0	0	0	0	0
	0%	48.0	55.4	80.1	55.4	71.4	109.6
	20%	355.9	364.5	386.7	364.5	376.8	396.6
20% TAW	No Irrigation	0	0	0	0	0	0
	0%	1.2	4.9	6.2	3.7	11.1	13.6
	20%	229.1	232.8	236.5	234.0	234.0	243.8
30% TAW	No Irrigation	0	0	0	0	0	0
	0%	0	0	0	0	0	0
	20%	7.4	2.5	7.4	7.4	12.3	14.8

Using the example above of a 10% ISWC level scenario, and with the aim of ensuring that irrigation is triggered when TAW reaches 20% (i.e., when enough rain has fallen to go from 10% TAW to more than 20% TAW but then the soil dries), the additional water requirement varies between 355.9 m^3/ha (364.5 m^3/ha) and 386.7 m^3/ha (396.6 m^3/ha), by the mid-century (end-century) period.

Similarly, with a 20% TAW irrigation threshold and for a 20% TAW ISWC level, water requirements are still substantial. In comparison, for the 30% ISWC level, irrigation needs drop to residual levels since irrigation is seldom triggered, on account of soil moisture being kept at today's levels, even under warming scenarios.

An extreme example of the importance of soil water content is the already mentioned scenario of irrigating when ISWC is under 10% TAW levels. In this case, setting the irrigation threshold to 0% TAW (thus using less water) would still require between 55.4 m^3/ha and 109.6 m^3/ha by the end of the century to reduce losses in productivity.

As expected, irrigation needs are higher with a higher threshold and lower ISWC. The scenario of a 10% ISWC level with a 20% TAW irrigation threshold is the one requiring more additional water during the growth phase. However, this is also the scenario leading to higher positive yield changes (Table 4). These can be explained by the triggering of (more) irrigation events at earlier stages of the plant growth phase when the above-mentioned couple of the ISWC and irrigation threshold is verified.

Conversely, the scenario where ISWC is kept at the current 30% TAW at the sowing date highlights the importance of soil water content. This scenario requires almost no additional water, either because irrigation is triggered rarely (at 20% TWA threshold) or not at all (at 0% TWA threshold) but still presents positive changes in barley productivity, even in a no-irrigation situation.

3.4.2. Mulching

The second adaptation strategy modelled was the application of mulches coupled with irrigation. The results of this strategy are reported in Table 6. Yield change and seasonal irrigation requirements are compared against values obtained for the same irrigation conditions but without the application of mulches (as per Tables 4 and 5 above).

Table 6. Effect of mulches on irrigation water needs and yields, expressed as the percentage change from the results obtained under the same conditions, without the application of mulches, for SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios and for mid- and end-century horizons. Green cells represent change in yields, and blue cells change in irrigation needs. The intensity of the colour is proportional to how positive or how negative that change is.

			2041–2070			2071–2100		
ISWC	**Irrigation Threshold**	**Parameter (Percentage Change)**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
10% TAW	0%	Yield	2.5	3.5	3.1	3.0	2.2	3.1
		Irrigation needs	−20.5	−8.9	−6.2	−13.3	−8.6	−11.2
	20%	Yield	4.5	2.4	4.5	3.5	3.0	3.8
		Irrigation needs	−3.1	−5.1	−4.1	−4.1	−4.3	−5.0
20% TAW	0%	Yield	4.6	5.0	4.6	4.0	4.1	5.8
		Irrigation needs	0.0	−25.0	−40.0	−33.3	−11.1	−18.2
	20%	Yield	5.4	4.4	6.9	5.1	5.9	6.5
		Irrigation needs	−1.1	−2.1	0.0	−1.6	−1.1	−1.5
30% TAW	0%	Yield	3.4	3.4	4.3	4.1	3.9	5.5
		Irrigation needs	0.0	0.0	0.0	0.0	0.0	0.0
	20%	Yield change	3.4	3.4	4.3	3.9	3.9	5.4
		Irrigation needs	−16. 7	0.0	0.0	−16.7	0.0	−8.3

The findings indicate that mulching is partially efficient in reducing irrigation needs while improving yields. The effect of mulches appears uniform throughout the time horizons, climate scenarios, and model parameterization. Mulching always lowers water needs while improving yields regardless of the ISWC level and irrigation threshold.

However, the effect of reducing water needs is more heterogeneous and affected by a much larger variance than increasing yields, with marked differences between climate scenarios, ISWC, and TAW irrigation thresholds. For example, the increase in yields promoted by the use of mulches never exceeds 10% (when compared to the irrigation-only strategy). Despite this, the reduction in irrigation water needs can reach up to 40% by the mid-century period under SSP5-8.5.

Mulches are more effective in reducing water needs for a 0% TAW irrigation threshold in the 10% TAW and 20% TAW ISWC parameterization and the 20% TAW irrigation threshold with a 30% TAW ISWC.

If annual inter-variability is factored in, these results open up the possibility that irrigation coupled with mulches could halt productivity losses in wetter years, for example, if the ISWC level is kept at least at 20% TAW by the sowing date. Mulching efficiency in absolute values can be found in Table S3.

3.4.3. Changing the Sowing Date

The last adaptation option tested was the change in sowing date (anticipation or delay) from the reference date of the 10th of November. Percentage changes in rainfed barley yield obtained for different modelled sowing dates are presented in Table 7 for all climate change scenarios, time horizons, and ISWC parameterizations.

Table 7. Effect of changing the sowing date on rainfed barley yield, expressed as the percentage change (%) from the yield obtained under the same conditions but with the sowing date on the 10th of November, for the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios and mid- and end-century horizons. Dates are in the format DD/MM. Green cells indicate positive changes; red cells indicate negative changes. The intensity of the colour isproportional to how positive or how negative that change is.

		15/10	25/10	04/11	14/11	24/11
Timeline	**ISWC**			**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

Results do not show a clear trend of improving barley yields with earlier or later sowing dates. Changes in productivity are within the −17.8% to +15.5% range, with only the 4th of November (one-week anticipation of sowing) showing positive values for all scenarios, time horizons, and ISWC parameterization.

By the mid-century period, the results show productivity improvements with up to 2 weeks earlier sowing dates but only for higher warming levels (SSP2-4.5 and 5-9.5) and lower ISWC (10% to 20%). However, this effect is not carried through to the end of the century, where productivity gains appear connected to a later sowing date of about 1 week.

These results may point to some positive gains of an earlier sowing date (in line with a warmer climate but not necessarily with a drier one). There is no clear evidence that an earlier or later sowing date would significantly improve barley yield in Almería.

4. Discussion

4.1. AquaCrop-OSPy Set Up

The results of our study illustrate how the AquaCrop-OSPy model can be parametrized and applied for the assessment of the long-term impact of climate change on barley crop yields in Almería province. A set of statistical methods was used to define the model's domain of applicability (paired *t*-test, Spearman and Pearson correlation coefficient, RMSE, and rRMSE) and to provide an estimation of a reference Initial Soil Water Content. The domain of applicability is determined by the approximations made throughout the modelling process that, while allowing for an easier application of AquaCrop-OSPy, do not allow for the retrieval of meaningful information on an inter-annual basis.

Our results show that AquaCrop-OSPy can provide a meaningful assessment of barley productivity even with uncalibrated crop parameters if a minimum period of 9 years is studied. A rolling average window above 9 years gives significant results with both Pearson and Spearman correlation coefficients and rolling average windows of 10 to 15 years show moderate-to-strong correlation coefficients (i.e., above 0.6), with the strongest correlation obtained for a rolling average of 13 years (above 0.8).

Error analysis showed that the value of 30% TAW is the best reference ISWC for the model parameterization of the baseline period, in Almería. This ISWC value had a good correlation coefficient with the historical observed data while minimizing the error. This value is not intended to represent the exact level of soil moisture when barley sowing happens, but it is rather a preliminary indication of this parameter extrapolated for modelling purposes. This value is expected to change from year to year and on a spatial basis. As shown in Table 3, the change in ISWC determines an absolute change in average yield of 1.59 tonne/ha between the lowest result (0.77, with 0% TAW) and the highest result (2.36, with 80, 90, and 100% TAW). It should be noted that the yield distributions simulated under all values of ISWC fall within the variance of the historical observed dataset, as shown in Figure S2.

Overall, our results expand the applicability of the AquaCrop-OSPy model to an area that was not studied before. In addition, our work suggests a novel modelling framework that can be applied to other case studies where a lack of data does not allow for crop parameter calibration.

4.2. Projected Impact of Climate Change on Rainfed Barley Yield

Our results indicate that the scenario with the greatest impact on rainfed barley production in Almería is SSP5-8.5, with more intense impacts at the end of the century. The results are highly dependent on the Initial Soil Water Content: a decrease in this parameter of up to 10% TAW translates into a maximum loss in average productivity up to −55.1%. For comparison, if the Initial Soil Water Content is 20% TAW, the average change is between −10.4% and −27.6%. This confirms the importance of this parameter for barley cropping in the Mediterranean, as highlighted by Cammarano et al. [11] and Al-Bakri et al. [15].

There is a visible overlap between yield distributions obtained with the different SSP scenarios. This pattern can be linked to the climatic projections outlined in Figure 3, which show that SSP1-2.6 and SSP2-4.5 do not have a marked difference, especially in precipitation. On the other hand, SSP5-8.5 shows different behaviour from the other two, particularly from 2060 onwards. This finding can help to explain the closeness in the results obtained with the different SSPs and the fact that at the end of the century, SSP5-8.5 showed an increased difference from the others.

The results obtained in this analysis support those of Bento et al. [12] who found that the radiative scenarios RCP8.5 and RCP4.5 (linked to SSP5-8.5 and SSP2-4.5) cause losses in barley production under a no-adaptation scenario in the mid-century period in the Iberian Peninsula. That study, however, pointed at the increase in temperatures as the main driver for such change in the south of Spain [12]. The difference compared to the present study might arise from the fact that Bento et al. [12] utilized a regression model based on the relationship between yields and climate variables. Having utilized a crop model, our study has instead a higher dependence on the crop's physiology. Similarly, Cammarano et al. [11] indicate mean yield changes for barley in the Mediterranean basin in the mid-century period and for an RCP4.5 scenario to range from −27% up to +8%, depending on the "wetness" of the scenario.

These findings compare with what was obtained under SSP2-4.5 (the scenario with the same radiative forcing as RCP4.5) in the mid-century period, +12% to –42%, and are also comparable with the yield changes estimated by Al-Bakri et al. [13] for barley yield change in Jordan in 2050: between +5% and −51%. Al-Bakri et al. [15] also indicate a grain yield change ranging (depending on the various analysed locations) from +6% to −17% under RCP4.5, between 2030 and 2050, and from +30% to −27% between 2080 and 2100. The respective results for RCP8.5 range instead from −9% to −58% (2030–2050) and +11% to −40% (2080–2100).

Regarding the reasons why the outlined changes in barley yield occur, as mentioned above, the main crop stress driver for the AquaCrop (and AquaCrop-OSPy) model is water availability [32]. In the model, this affects the crop's physiology in four areas, canopy growth, stomata conductance, canopy senescence, and root deepening, with the first being the most sensitive [32]. Operatively, AquaCrop slows the crop's growth in proportion to water stress, and, if the stress is severe enough, the plant's stomata are modelled to close, eventually triggering senescence. AquaCrop links this latter occurrence to a reduction in photosynthetic activity [32]. A reduction in stomatal conductance is also among the main drought-induced risks identified in the literature [32]. These would, therefore, be the main physiological reasons determining barley yield reduction in Almería which are deducible from the model.

4.3. Adaptation Strategies

4.3.1. Irrigation

The results indicate that irrigation needs will be higher in cases of lower Initial Soil Water Content and if a higher irrigation threshold is set. These conditions will lead to more irrigation events.

When determining the irrigation needs, the importance of the Initial Soil Water Content appears to be greater than the SSP scenario or the time horizon, as shown in Figure 4. This parameter determines how early irrigation events are triggered, and the water available to the plant, particularly in the earliest stages of its life which are crucial for its development and to avoid crop failure.

As expected, the results indicate that increased irrigation causes increased yields. The scenario with more important irrigation needs, the 10% TAW ISWC with a 20% TAW irrigation threshold, is also the one that provides a greater increase in yields, reaching values that exceed +20% in crop productivity. The water needs, in this case, are greater than 300 m^3/hectare, which, considering the areas sown with barley in Almería, result in ~3 hm^3 of water, representing around 1.5% of the yearly groundwater resources available in Almería in 2022 and around 3% of the yearly superficial water resources of Almería in 2022 [65]. However, these percentages are 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 [65].

If interested in reducing water needs to the minimum, the case of 10% TAW water content at sowing, with an irrigation threshold of 0% TAW (only giving water to avoid going below the Permanent Wilting Point), shows that the yield losses would exceed 30%. On the other hand, a 30% TAW soil water content at sowing would significantly increase crop productivity with extremely low water requirements. However, as shown in Figure 4, a situation where the ISWC would stay similar to the present situation is not supported by evidence from any of the climate projections.

4.3.2. Mulching

The application of mulches effectively reduces irrigation needs and increases productivity. Mulches can improve yields by up to 6.9% and reduce irrigation needs by up to 40%. The efficiency appears to be slightly higher when the ISWC is set to 20% TAW, independent of the time horizon or climate change scenario. The performance of mulching is rather uniform throughout all scenarios analysed, always increasing yield while reducing irrigation water needs.

These findings support claims about the effectiveness of mulching for climate change adaptation in the region, as suggested by the Junta de Andalucía. Consejería de Agricultura Ganadería Pesca y Desarrollo Sostenible [66] and the Unión de Pequeños Agricultores y Ganaderos [37].

However, caution is required when analysing these results. The barley crop parametrization modelled in AquaCrop-OSPy has a shorter growth cycle than the actual one used in the region, therefore only capturing winter and early spring. This in turn means that only the months with limited potential evapotranspiration are considered, not allowing for a full assessment of the real potential of this field management solution. The inclusion of periods of more intense evapotranspiration would be required to have a clearer picture of the mulching efficiency for barley production in the region.

4.3.3. Changing the Sowing Date

The findings of our study do not show a clear pattern that suggests additional benefits of introducing an earlier or later sowing date for rainfed barley in Almería, opposing widespread beliefs of adaptation practitioners in the area [37]. Instead, they indicate how the window for optimal yields becomes smaller when the stress on the plant is higher. This finding captures the potentially more erratic behaviour of rainfall caused by climate change [3], shortening the window of optimal rainfall availability for the plant, which allows for optimal growing in earlier stages and making the losses caused by sowing at other times more significant.

However, our work can only capture the effects of rainfall during the crop's growth and not before sowing, when it accumulates in the soil and creates the preconditions for planting, as reflected by the importance of ISWC. This caveat in the modelling approach can significantly affect the sowing date results. For example, Russel [67] stated that there is a need for at least 25 mm of cumulative rainfall before sowing. In reality, this condition could push the sowing date later, due to the overall reduction in precipitation (and assuming a similar seasonal distribution), but this is something the model cannot capture due to the limitation mentioned above.

Our results can be compared to what was outlined by Cammarano et al. [11] who showed how later sowing dates could benefit yields under a "wet" scenario, therefore apparently departing from the results of this work. However, the same author states that later sowing dates can also lead to crop losses under a "dry" scenario [11] which is in line with our evidence. This partial difference in results can be explained by the fact that Cammarano et al. [11] explicitly considered cumulative rainfall before sowing as a parameter, adding a variable not modelled in our study. In general, however, Cammarano et al. [11] state how the usual barley sowing window in the Mediterranean basin (from September to December) will still be relevant in the future, confirming our findings.

An additional finding of our study is that scenarios with higher soil water content at sowing time result in a lower variability of yields, especially in the mid-century period, reinforcing the importance of ISWC. This indicates that soil moisture can also play a monitoring and forecasting role, allowing for easier planning of barley agriculture in Almería and potentially elsewhere in the Mediterranean.

4.3.4. Implications of the Results

The first indication that emerges from our results 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 barley production in Almería.

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 effective adaptation pathway is irrigation. Evidence reported here shows that it could be possible to implement irrigation without excessively further impacting the water resources balance of the province. In particular, coupling this practice with mulching reduces irrigation needs and can help the planning of a future transition from rainfed to irrigated barley production.

Irrigation is a water resource-intensive strategy, which could create additional pressure on an already water-stressed region like Almería. Ensuring good soil water content at the time of sowing appears to be a fundamental step, and acting towards limiting soil water loss before changing to irrigated agriculture emerges as a sensible approach.

Our results show that adaptation is possible and effective. However, adaptation carries a cost, quantified here in terms of water resources, but that will also require translation into (socio-)economic costs. Decisions linked to water management in the future will be based on the province's will to adapt barley production to climate change. In turn, it should be acknowledged that adaptation choices are surrounded by many complexities at the provincial level, including environmental and societal considerations. Elaborating on the possible scenarios linked to such choices is outside the scope of this work. The evidence presented in this work can not only help support decision-making processes that look to the importance of barley as the main field crop in Almería but also future studies about climate adaptation in Almería's agricultural sector.

5. Limitations and Future Research

Our study has various limitations that have been made explicit in the paper.

The most significant limitation is the use of uncalibrated barley parameters in AquaCrop using the standard parameters available for a short-cycle barley variety grown in Ethiopia. This introduces uncertainties linked to the crop's responses to climate occurring outside the modelled growing season (i.e., in late spring). Future work in this area should carry out a preliminary calibration to improve the accuracy of the results. Such results could be compared to the ones illustrated in this paper to evaluate the benefits of crop calibration. The modelling approach adopted does not capture the inter-annual variability of crop growth. While this approximation is suitable for the paper's focus on multi-year trends, it does not allow for the analysis of finer time scales. This limits the applicability of this approach to long-term analyses. The results are therefore intended as a quantification of a range of probable future trends in rainfed barley growth in Almería. Future research can improve the modelling framework and investigate inter-annual variability in rainfed barley yields.

Secondly, the accuracy of modelling cropland management practices associated with climate adaptation in Almería could benefit from the use of field data for validation, e.g., calendar types, sowing dates, crop characteristics, or in its absence, from the interaction with local stakeholders.

Furthermore, the modelling used average values for the whole of the Almería province, thus not allowing for the possibility of studying spatial patterns in barley productivity change. Future studies could implement a modelling strategy based on pixel data, such as the one proposed by de Roos et al. [33].

Then, in our study, adaptation strategies were kept identical across climate change scenarios. However, different scenarios also include different socio-economic, technological, and behavioural developments. Future research would benefit from modelling adaptation strategies that reflect these different narratives. This should come in tandem with an overall improvement in the accuracy of the modelling framework.

Lastly, this paper focuses on the effect of climate change on overall rainfed barely yields in Almería province, as climate was identified as the key variable of interest for local stakeholders. A deep investigation of the physiological reasons that cause such changes in yields is beyond the scope of the present study. Future studies might be interested in using the results of this study as a basis for the investigation of the agronomic aspects of such yield change.

We plan to address these limitations in future works, using the results and methods of this paper as a basis.

6. Conclusions

This paper applied the AquaCrop-OSPy model to evaluate the impact of climate change on rainfed barley cropping in the previously unstudied province of Almería, Spain. In this study, irrigation, mulching, and changing the sowing date were included in the modelling to evaluate their efficacy as climate change adaptation solutions.

Our work suggests a modelling framework for AquaCrop-OSPy without using field data or locally recalibrating the barley parameters. Such an approach was evaluated to be effective in retrieving meaningful information if at least 9 years of data were analysed. A reference Initial Soil Water Content, in this case identified as 30% TAW, allowed for finding a distribution of modelled yield that better matched the historical observed dataset.

Subsequently, AquaCrop-OSPy was run for two future time periods (2041–2070 and 2071–2100) under three climate change scenarios (SSP1-2.5, SSP2-4.5, and SSP5-8.5). To account for possible decreases in soil water availability, varying Initial Soil Water Content levels (10%, 20%, and 30% TAW) were considered for each climate change scenario and time horizon.

Results indicate a possible reduction of −55.1% at the end of the century, for a 10% TAW soil water content at sowing. In the case of an Initial Soil Water Content of 30% TAW, the results indicate yield increases of up to 14% and no decreases in average yields, for the same time horizon. Therefore, it can be concluded that the most important parameter determining future rainfed barley productivity changes is the Initial Soil Water Content (ISWC).

Irrigation emerges as an effective adaptation option in cases of reduced Initial Soil Water Content but carries the burden of exploiting already limited water resources. However, such water requirements were quantified to be slightly less than 400 m^3/ha during the crop growing season, which would account for a minimal percentage of the water resources of Almería province, even considering climate change.

Two additional adaptation strategies were modelled. Mulching was effective in limiting irrigation water needs and partially improving yields. Anticipating or delaying the sowing dates of rainfed barley, on the other hand, was not shown to improve rainfed barley production. The findings, however, support the conclusion that the ideal sowing window might be reduced in the future.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/atmos15050606/s1, Figure S1: Aerial picture of Almería's landscape (own photograph taken in January 2024). Figure S2: AquaCrop-OSPy rainfed barley productivity simulation results for the baseline period with different Initial Soil Water Contents, compared to the historical observed dataset. Table S1: P-values for the Pearson and Spearman correlation coefficient between the historical observed dataset and the modelled runs obtained with different rolling average windows. Bold values indicate significant correlation (*p*-value lower than 0.05). Table S2: Percentual changes in average barley productivity at mid-century and end-century, under SSP1-2.6, SSP2-4.5 and SSP5-8.5 compared to the average of the baseline period. Bold values indicate significant changes according to a paired *t*-test with a significance threshold of 0.05. Table S3: Effect of mulches on irrigation water needs (m^3/ha) and yields (ton/ha), expressed as the absolute change from the results obtained under the same conditions, but without the application of mulches, for SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios, and for mid- and end-century time horizons.

Author Contributions: Conceptualization, F.S., B.R., R.E.C., L.B. and T.C.L.; methodology, F.S., B.R., R.E.C. and T.C.L.; software: F.S.; validation, B.R. and R.E.C.; formal analysis, F.S.; investigation, F.S., B.R., R.E.C., A.R., G.F. and T.C.L.; resources, A.R., G.F. and R.O.; writing—original draft preparation, F.S. and T.C.L.; writing—review and editing, F.S., B.R., R.E.C., A.R., R.O., L.B. and T.C.L.; visualization, F.S.; supervision, L.B. and T.C.L.; project administration, F.S. and T.C.L.; funding acquisition, T.C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out within the framework of the European project RethinkAction, that received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101037104. doi: 10.3030/101037104.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original data presented in the study are openly available in GitHub repository "impacts-barley-Almería" (https://github.com/frasare/impacts-barley-Almer%C3%ADa, accessed on 12 May 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

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