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Future Changes in Rice Bioclimatic Growing Conditions in Portugal

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Abstract: Rice is a historically important crop in Portugal. This crop development and production strongly depend on atmospheric conditions in the growing season. Given the strong dependence of climatic conditions, climate change may pose a significant risk for future rice production. In the present study, a high spatial resolution bioclimatic characterization over the main rice producing region in Portugal was performed for the recent past (1950–2000) and for the future (2041–2060) under four different anthropogenic forcing scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). This zoning is performed by using eight bioclimatic indices, based on temperature and precipitation, using a very high resolution gridded dataset (Worldclim). For the future period, an 11-member global climate model ensemble was used, also taking into account model/scenario uncertainties and bias. Additionally, a new index was developed to incorporate the main features of temperature and precipitation at each rice field level. Under recent past climates, a clear north–south gradient in temperature and precipitation is apparent, with the regions of Tejo and Sado presenting higher temperatures and lower precipitation than the Mondego and Vouga regions. Additionally, there is a coastal–inland effect due to the Atlantic Ocean influence. Under anthropogenic climate change, all indices point to annual higher temperatures and lower precipitations across all rice producing regions, accompanied by increased seasonality. Furthermore, the rise of summertime temperatures may substantially increase water demands, which, when unmitigated, may bring physiological problems in the crop development. We conclude that climate change may negatively impact the viability of rice production in Portugal, particularly taking into account the national grown varieties. Thus, adequate and timely planning of suitable adaptation measures are needed to ensure the sustainability of this historically important food sector.

Keywords: rice; Portugal; climate change; Euro-Cordex; representative concentration pathways

1. Introduction

Rice (*Oriza sativa* L.) is the second most widely cultivated and consumed cereal in the world, behind maize. Rice is the staple food for nearly two-thirds of the world's population [1]. Given the extent of cultivated area and the large amount of population that depends on their own crop cultivation for daily food, this crop may be considered of extreme importance. In effect, world average productivity of rice has been gradually increasing from 3.89 t ha^{-1} in 2000 to 4.40 t ha^{-1} in 2011 [2]. India and China are the countries with the largest rice area in the world (44×10^6 ha and 30×10^6 ha, respectively). These two countries are responsible for an annual production of over 300×10^6 tons [2]. In the EU, around three million tons of paddy rice are produced per year in an area of 466,000 ha, with an average yield of 6.4 t ha^{-1}.

Portugal (Figure 1) currently has an area devoted to rice cultivation of about 30 × 10^3 hectares, producing approximately 180 × 10^3 tons of rice per year, mainly in paddy fields, which represents about half of its domestic consumption [3]. Portugal is the EU fourth rice producer, accounting for about 6% of rice production [4]. This crop has a high socioeconomic relevance for the country. In fact, Portugal has the highest consumption per capita in all of Europe, of about 16 kg/yr, which is about three times the European average [4]. The production area is mainly concentrated in lowlands along the Tejo (Tagus) river and Sorraia (Tejo tributary) (14,000 ha), as well as along the Sado (9000 ha) and Mondego (6000 ha) river valleys [3] (Figure 1). In Portugal, rice is grown under irrigated conditions, while farms tend to be of medium to large size, with intensive mechanization. A large percentage of the rice produced in Portugal corresponds to the round grain variety "Carolino" (Japonica) and its main varieties are "Aríete" and "Euro" [5] but also "Agulha" (Indica) rice, with a characteristically elongated grain [6].

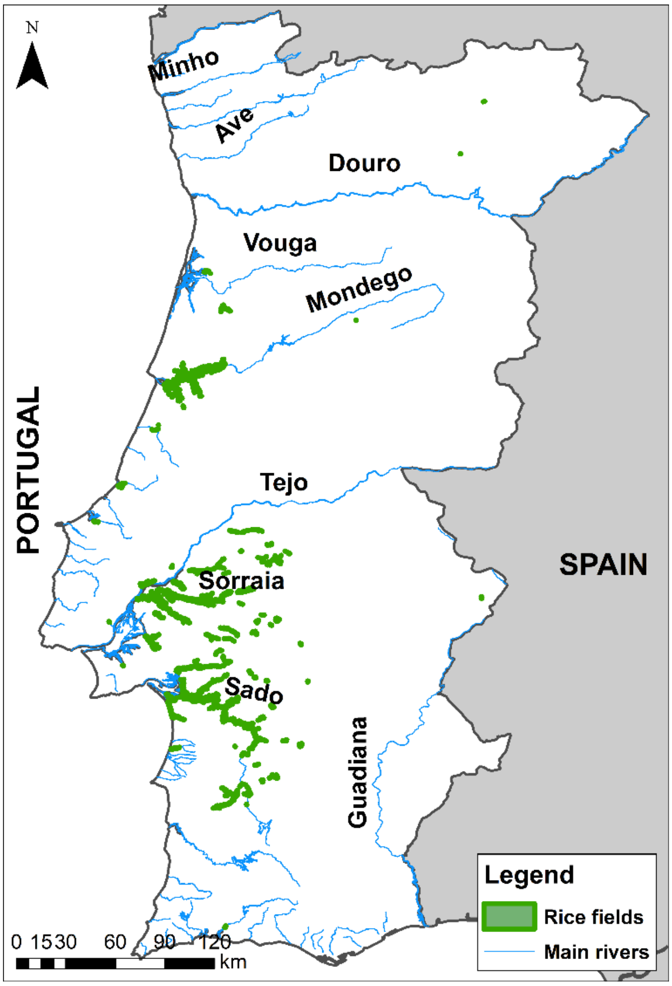

Figure 1. Rice field distribution in Portugal following the CORINE land cover dataset. The main rivers in Portugal are also represented.

Rice development and production strongly depend on temperature conditions in the growing season. Temperature is a major factor for plant photosynthesis, considering that physiological activity of plants under temperature stress may be strongly reduced [7]. Excessive temperatures can result in a decline of photosynthesis and also a decrease in the allocation of dry matter to shoots and roots [7]. However, temperature stress in plants is a complex function of intensity and duration [8]. Critical temperatures differ according to cultivars, duration of critical temperature, diurnal changes, and physiological status of the plant.

Given the strong dependence of temperature conditions, climate change may pose a significant risk for rice production [9–12]. Future projections for Portugal point to an increase in temperature, which may affect food production [13–19]. State of the art climate models project that global surface air temperatures may increase by up to 5 °C in the next few decades, depending on the specific future scenario [20]. Increases in temperature will probably offset the likely benefits of increasing atmospheric concentrations of carbon dioxide (CO_2) on crop plants. In future climatic conditions, rice yield may be reduced, depending on the growing-season environmental conditions, as present-day increasingly high temperatures have been associated to reductions in rice yield in many rice-growing areas [21,22].

In addition to the increase in temperature under future climates, projections also point to a general decrease in precipitation throughout the Mediterranean basin area [20]. The resulting increase in aridity should have negative repercussions on this crop, given that current rice production systems rely on ample water supply and are thus quite vulnerable to drought stress. In effect, water stress is the largest constraint to rice production in the rainfed systems. At the whole plant level, soil water deficit is an important environmental constraint, negatively influencing all the physiological processes involved in plant growth and development. Given the threats to this vulnerable crop in a warmer world, it is imperative to understand the impacts of climate and climate change on these important food crops in Portugal.

To study recent past climate and to assess possible climate change impacts, spatially interpolated climate datasets may represent a key tool [23]. Particularly, high spatial resolution datasets are of significant importance, since coarser resolutions may not properly capture environmental variability within agronomic regions. This is particularly relevant for regions with steep climate gradients, which is the case of Portugal, particularly the north–south and coastal–inward gradients. There are very diverse rice growing conditions in Portugal (Figure 1). Bioclimatic indicators, which combine key climatic factors (such as temperatures and precipitation) at very high resolutions (<1 km), may allow a suitable characterization of recent past and future climate change projections for rice growth. Assessing the bioclimatic conditions for rice growth under future scenarios is still incipient in Portugal and deserves further research in order to assist stakeholder's decision making.

The present study aims at analyzing the impacts of climate change on rice bioclimatic growth conditions in Portugal. As such, the objectives of the present study are five-fold—(1) to analyze recent-past bioclimatic indicators over the Portuguese rice growing areas using historical high-resolution gridded datasets, (2) to compute future changes of these bioclimatic indicators using a large ensemble of high-resolution climate models, (3) to analyze uncertainties found in these climate change projections, (4) to develop a metric that combines all bioclimatic indicators, allowing to establish the impact of climate change on future rice growing zones, and (5) to discuss potential adaptation measures.

2. Materials and Methods

2.1. Rice Fields

In order to assess the distribution of rice fields in Portugal, the CORINE Land Cover (CLC, v18.5.1) was used. This dataset is derived from satellite imagery and mapping of land inventories, providing land usage classes over most of Europe, and was previously shown to accurately represent the Portuguese land cover [24]. Rice field centroids were extracted for subsequent processing. All computations were herein performed using the centroids, which represent a rice field (cf., Figure 1). A more detailed analysis was also performed on the main rice producing regions of the country, which are located within the Mondego, Sado, Tejo, and Vouga river basins (Figure 1). For this purpose, the river basins in Portugal were obtained from the "Sistema Nacional de Informação de Recursos Hídricos" (SNIRH).

2.2. Bioclimatic Datasets

A set of bioclimatic indices (Table 1) were obtained from a very high resolution climate dataset, produced by the WorldClim project [25]. This dataset has previously been validated against other observational datasets over Portugal [26], showing high correlations throughout the country. This gridded dataset provides several bioclimatic indicators based on temperatures and precipitation (Table 1), over a 0.008° × 0.008° latitude-longitude grid (~1 km). The main indices were annual mean temperature (°C; T_{annual}), temperature seasonality (°C; T_{season}), mean temperature of warmest quarter (°C; T_{warm}), mean temperature of coldest quarter (°C; T_{cold}), annual precipitation (mm; P_{annual}), Precipitation Seasonality (%; P_{season}), precipitation of wettest quarter (mm; P_{wet}), and precipitation of driest quarter (mm; P_{dry}). These indices were computed for both recent-past (1950–2000) and future (2041–2060) under four different scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). The use of different RCPs in the present study allows accounting for scenario uncertainty [27].

Table 1. List of the bioclimatic indices selected in the present study, along with the descriptions of the seasonality indices.

Ref	Bio Climatic Index	Description
T_{annual}	Annual Mean Temperature (°C)	Average temperature over 12 months
T_{season}	Temperature Seasonality (°C)	Standard deviation of the 12 mean monthly temperature values, multiplied by 100 (Standard deviation *100)
T_{warm}	Mean Temperature of Warmest Quarter (°C)	The warmest quarter of the year is firstly identified followed by the calculation of the average temperature for the 3 months in the warmest quarter
T_{cold}	Mean Temperature of Coldest Quarter (°C)	Same as T_{warm} but for the coldest quarter
P_{annual}	Annual Precipitation (mm)	Sum of the precipitation of each of the 12 months in a year
P_{season}	Precipitation Seasonality (%)	Coefficient of variation of the 12 monthly precipitations
P_{wet}	Precipitation of Wettest Quarter (mm)	The wettest quarter of the year is firstly identified followed by the calculation of the precipitation for the 3 months in the wettest quarter
P_{dry}	Precipitation of Driest Quarter (mm)	Same as P_{wet} but for the driest quarter

For future climates, data was generated from 11 different Global Climate Models (GCM) (Table 2). Multi-model ensembles account for the model uncertainty [27], which is inherent to these simulations due to different parameterizations and different modelling approaches, among others. In effect, model uncertainty resulting from different model parameters may lead to different outcomes [28] and different interpretations of climate change impacts. Thus, the projected climatic signal for a given period and region may strongly depend on the model and on the emission scenario. Furthermore, this approach also allows developing ensemble statistics for climate projections, as the quantification of the uncertainty associated to climate change projections is extremely important.

In this dataset, the recent past data was obtained from a number of observational datasets (weather station data) and was spatially interpolated to a <1 km grid through thin-plate smoothing splines [25]. Downscaling of the GCM data to the <1 km grid was accomplished using the delta method [29]. This method takes into account the biases in future climate projections. The above-mentioned variables were then extracted over the Portuguese mainland (649 × 865 grid cells), followed by the extraction of the individual pixels for each rice field.

Table 2. Summary table of all Global Climate Models (GCM) used in this study. The corresponding acronyms and institutions are listed, along with the relevant references.

GCM	Institution	References
BCC-CSM1-1	Beijing Climate Center Climate System Model	[30]
CCSM4	National Center for Atmospheric Research	[31]
GISS-E2-R	National Aeronautics and Space Administration	[32]
HadGEM2-AO	UK Met Office	[33]
HadGEM2-ES	UK Met Office	[34]
IPSL-CM5A-LR	IPSL Climate Modeling Center	[35]
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology	[36]
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology	[36]
MIROC5	Japan Agency for Marine-Earth Science and Technology	[37]
MRI-CGCM3	Meteorological Research Institute	[38]
NorESM1-M	Norwegian Climate Centre	[39]

2.3. Uncertainty Measures (Model vs Scenario)

As was previously mentioned, the present study covers a representative sample of climate models (11) and future scenarios (4). This methodology takes into account not only all the different emission scenarios but also the different model parameterizations, initializations, physics, and numerical modelling approaches, which cover a large part of the uncertainties inherent to climate model simulations. Nonetheless, these inherent uncertainties must be carefully analyzed and quantified. In order to assess uncertainties tied to the model ensemble and to the future scenarios, their corresponding standard deviations (SD) were computed separately. The model SD (SD of the models after averaging over all scenarios) and the scenario SD (SD of the scenarios after averaging over all models) were then compared, thus providing a measure of uncertainty found in the future climate projection for each rice field centroid. By comparing model and scenario SD it will be possible to determine the main source of uncertainty in future climate projections. The correlation coefficients between these two types of uncertainty was also determined in order to assess the potential coherence between them.

2.4. Combined Index

In order to better discriminate the current and future bioclimatic conditions of each rice growing region in Portugal, an innovative category analysis was also carried out. This single, multipurpose index provides combined information (CombI) regarding regional bioclimatic characteristics. This index is based on the values of annual mean temperature and annual precipitation at each region, as described in Table 3. CombI comprises only six different categories (Table 3), which simplifies its mapping over large areas and allows an easier regional comparison. As such, the index was then computed on a spatial scale for each rice field, for the recent past, and for each future scenario.

Table 3. Combined index (CombI) category description and corresponding threshold values for annual mean temperature and annual precipitation totals.

Annual Mean temp. (°C).	Annual Precipitation (mm)	CombI
≥17	<700	1—Warm/Dry
≥17	≥700 <900	2—Warm/Moderate
≥17	≥900	3—Warm/Wet
<17	<700	4—Cool/Dry
<17	≥700 <900	5—Cool/Moderate
<17	≥900	6—Cool/Wet

3. Results

Figure 2a shows the annual mean temperature (T_{annual}) over the main rice producing regions in Portugal. A clear north-south gradient of the T_{annual} is clear, with Vouga and Mondego rice fields showing lower temperature than Tejo and Sado. Sado currently shows the highest overall values (> 17 °C), whereas Vouga presents the lowest values (<15.5 °C). Regarding temperature seasonality (Figure 2b), apart from the north-south gradient, a coastal-inland gradient is found, with a significant increase in seasonality in the inner areas, compared to the coastal areas. This is mostly due to the Atlantic Ocean influence, which results in a more moderate (maritime) climate in the coastal areas of the country. The T_{warm} (Figure 2c) reaches values of 23–24 °C in Sado, 21–23 °C in Tejo, 20–22 °C in Mondego, and 19–21 °C in Vouga. For T_{cool} (Figure 2d), although the patterns are similar to T_{warm}, this metric is more susceptible to the Atlantic influence, showing a clear coastal-inland gradient, particularly in the Tejo and Sado rice growing areas. T_{cool} shows values of 10–10.5 °C in Vouga, 10.5–11.5 °C in Mondego, and 11.5–12.5 °C in Tejo and Sado.

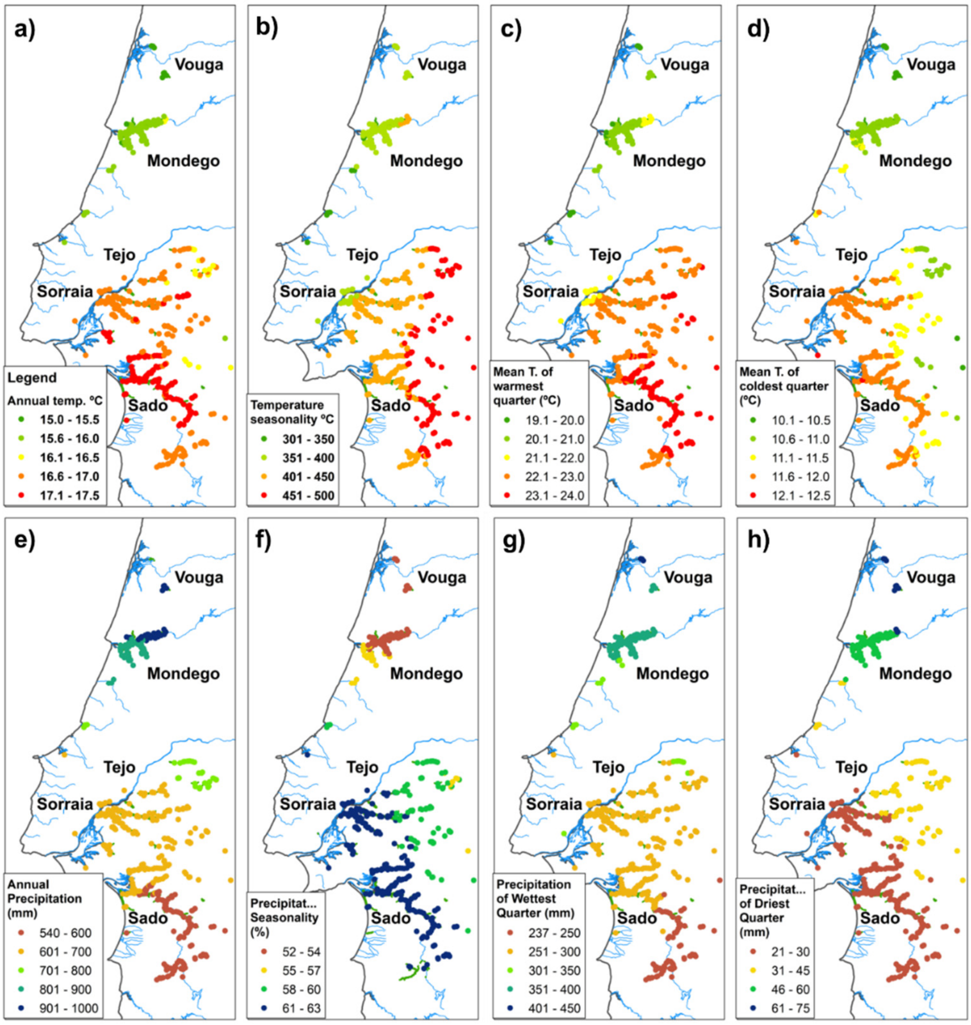

Figure 2. Maps representing the recent-past (**a**) annual mean temperature, (**b**) temperature seasonality, (**c**) mean temperature of the warmest quarter, (**d**) mean temperature of the coolest quarter, (**e**) annual precipitation, (**f**) precipitation seasonality, (**g**) precipitation of the driest quarter, and (**h**) precipitation of the wettest quarter.

Regarding the annual precipitation (P_{annual}) (Figure 2e), a north–south gradient is also present, with the Vouga and Mondego presenting higher levels of precipitation than Tejo and Sado. In effect, it is clear that the warmest areas are also the driest. Sado P_{annual} values range from 500 to 700 mm, from 600 to 800 mm in Tejo, and from 800 to 1000 mm in Mondego and Vouga. Precipitation seasonality (Figure 2f) reveals higher values in the coastal areas of Sado and Tejo and overall lower values in Vouga and Mondego. Regarding P_{wet} (Figure 2h), Sado shows the lowest values (<250 mm), 250–300 mm for Tejo mm, and 350–400 mm for Mondego and Vouga. P_{dry} (Figure 2g) tends to show similar patterns to P_{wet} but with much lower values and a stronger coastal–inland gradient. Sado shows the lowest values (<30mm), followed by Tejo (20–45 mm), Mondego (45–60 mm), and Vouga (~70 mm).

Figure 3 shows the distribution of values for all the rice regions in Portugal, for the recent-past and for each future scenario (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), as well as for each bioclimatic indicator. Overall, for the temperature base indices, i.e., T_{annual} (Figure 3a), T_{warm} (Figure 3a), and T_{cool} (Figure 3b), there is a clear shift toward higher temperature across all future scenarios. The future distribution tends to preserve the same shape (skewness) of the recent past, despite the shifting to a more leptokurtic shape. RCP8.5 shows the strongest shift, while RCP2.6 the weakest signal. RCP4.5 and RCP6.0 show intermediate values between the other extreme scenarios. For the precipitation based indices, i.e., P_{annual} (Figure 3e), P_{dry} (Figure 3h), and P_{wet} (Figure 3h), these point to a significant shift to lower precipitations under all future scenarios. For P_{wet} (Figure 3h), the shift is less pronounced in terms of mean, but with higher kurtosis. Regarding seasonality in T_{season} (Figure 3b) and P_{season} (Figure 3f), both suggest an increase in the range, thus indicating enhanced variability under future climates.

Figure 4 shows the uncertainty linked to the abovementioned projections. Model uncertainty and scenario uncertainty are represented by the respective standard deviation in T_{annual} (Figure 4a), P_{annual} (Figure 4b). First, it becomes clear that the values associated to model uncertainty are generally higher than those associated to scenario uncertainty, although both values tend to be low. For T_{annual}, values are within the range of $0.20 < SD < 0.25$ for scenario SD and $0.80 < SD < 0.90$ for model SD. For P_{annual}, values range within the interval $10 < SD < 20$ for scenario SD and $55 < SD < 80$ for model SD. Nonetheless, these two uncertainties are expected to be significantly and highly correlated ($0.68 < r < 0.96$). As such, it can be assumed that the current climate change projections are indeed affected by a small level of uncertainty, taking into account the 11-member model ensemble and the four future scenarios.

For the sake of succinctness, given that all future scenarios point to similar shifts in distribution and the scenario uncertainty in relatively low, all analyses will henceforth be performed on RCP4.5 (an intermediate climate scenario). Figure 5a presents the shifts in values of T_{annual} vs. P_{annual} for each rice producing region. It is clear that all regions will shift toward warmer and dryer climates under future scenarios. Sado will present the highest values of temperature and the lowest values of precipitation, followed by Tejo, Mondego and Vouga. In effect, measuring the Euclidian distance between the average pairs of T_{annual} vs. P_{annual} in the recent past and future, the region with the strongest climate change signal can be identified (Table 4; the Euclidean distance between the centroid of each pair T_{annual} vs. P_{annual}, under future and recent-past). In this way, Vouga will present the strongest shift from the recent-past to the future, followed by Mondego, Tejo, and Sado. This ranking is strongly influenced by the higher precipitation loss (drying trend) in Vouga and Mondego, compared to Tejo and Sado. Although Sado and Tejo are projected to become the warmest and driest regions, their changes will not be so pronounced as in Vouga and Mondego. Figure 5b shows the graphical delimitations of the new CombI. Its thresholds and descriptions are also shown in Table 3. The CombI is divided into six classes, ranging from 1 – Warm/Dry to 6 – Cool/Wet.

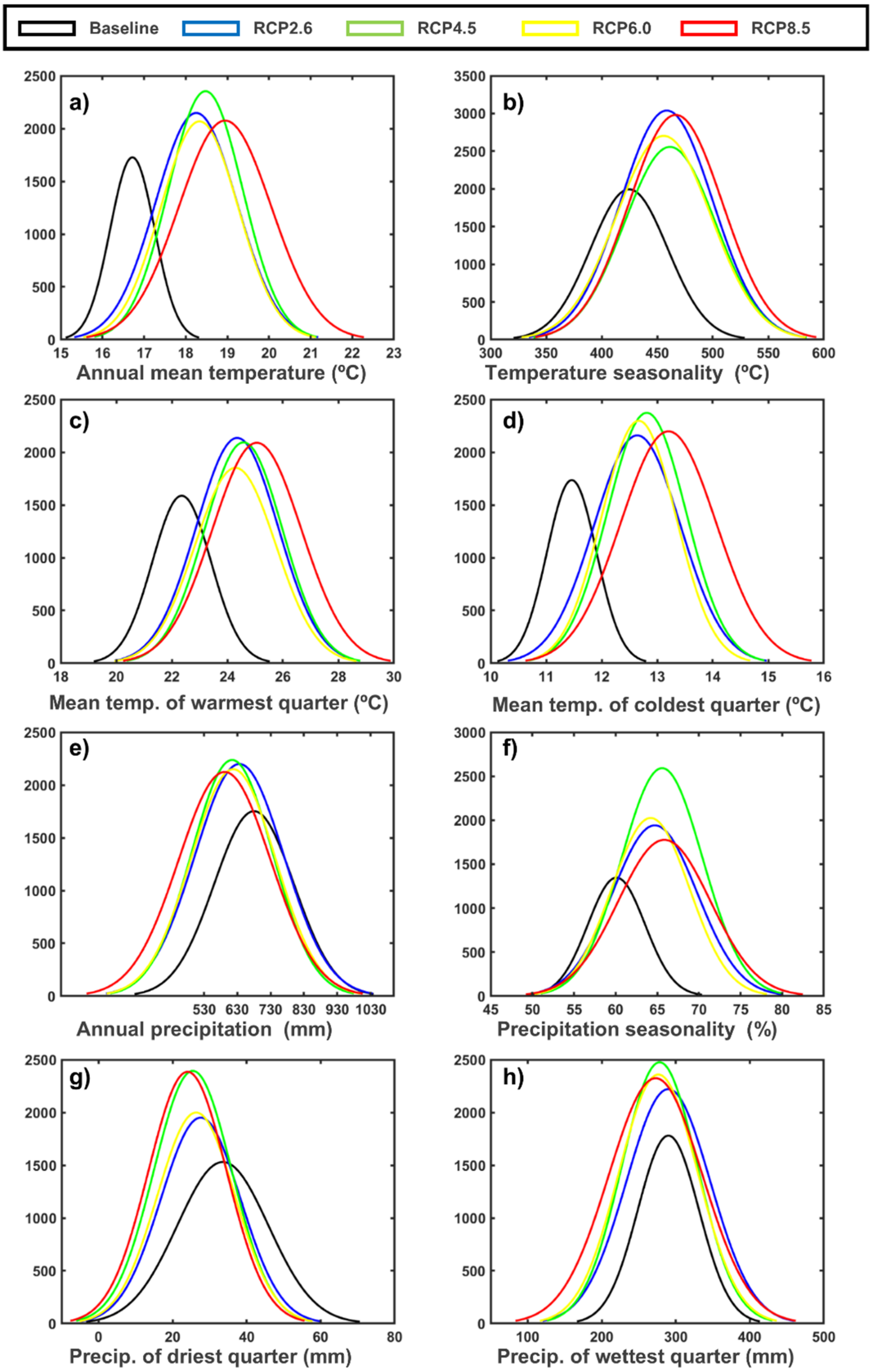

Figure 3. Distribution plots (kernel-smooth), representing the recent past and future scenarios for (**a**) annual mean temperature, (**b**) temperature seasonality, (**c**) mean temperature of the warmest quarter, (**d**) mean temperature of the coolest quarter, (**e**) annual precipitation, (**f**) precipitation seasonality, (**g**) precipitation of the driest quarter, and (**h**) precipitation of the wettest quarter. The y-axis represents the number of occurrences.

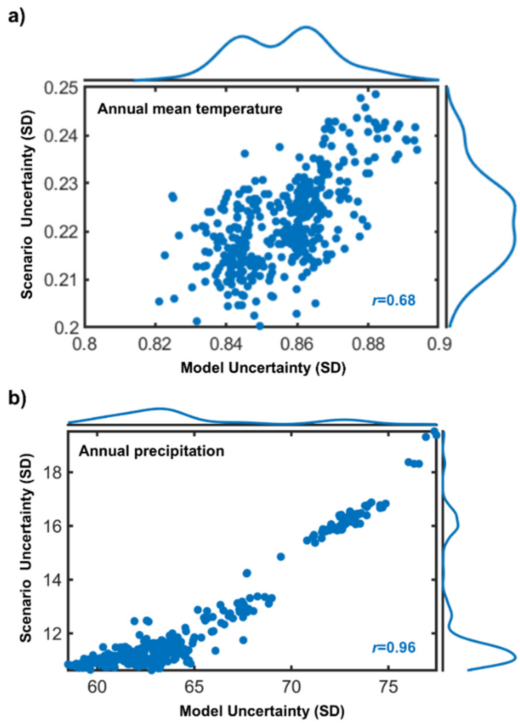

Figure 4. Scatterplots for the scenario and model uncertainty (SD: standard deviation) in the (**a**) annual mean temperature and (**b**) annual precipitation over the Portuguese rice fields. The correlation coefficient between the two types of uncertainties is also shown. The distribution curves are also plotted.

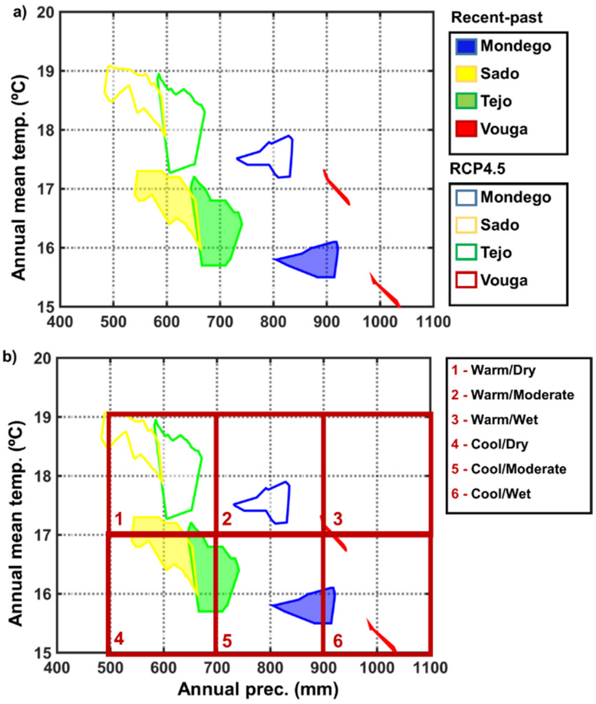

Figure 5. (**a**) Graphical representation of the annual mean temperature (in °C) vs. annual precipitation totals (in mm) for each rice producing region in Portugal (Mondego, Sado, Tejo, and Vouga), for both the recent-past (1950–2000) and future (2041–2060) under RCP4.5. (**b**) The same as in (**a**), but with the two-dimensional ranges of the six classes of the combined index (cf. legend for details).

Table 4. Ranking of the rice growing regions most affected by climate change under RCP4.5 (depending on the mean Euclidean distances between future and recent-past for the selected metric pairs).

	Region	Mean temp. vs Annual prec.
1	Vouga	92
2	Mondego	82
3	Tejo	65
4	Sado	60

Figure 6 shows the spatial distribution of the CombI in the recent past (Figure 6a) and under RCP4.5 (Figure 6b). For the recent-past, many rice fields in the Sado and Tejo regions are already in class 1 (Warm/Dry). Nonetheless, some small areas within these regions are still in class 4 (Cool/Dry) and class 5 (Cool/Moderate), which indicates lower temperatures and more humid climates. The Mondego region typically presents two types of CombI, class 5 (Cool/Moderate), south of the Mondego river, and class 6 (Cool/Wet) northwards of the river. The Vouga region is typically in class 6 (Cool/Wet). Under future climates, a clear shift of most of Sado and Tejo to class 1 is found, highlighting a warming and drying trend, whereas Mondego and Vouga show typical class 2 (Warm/Moderate). These later regions will benefit from moderate humid climates under future scenarios.

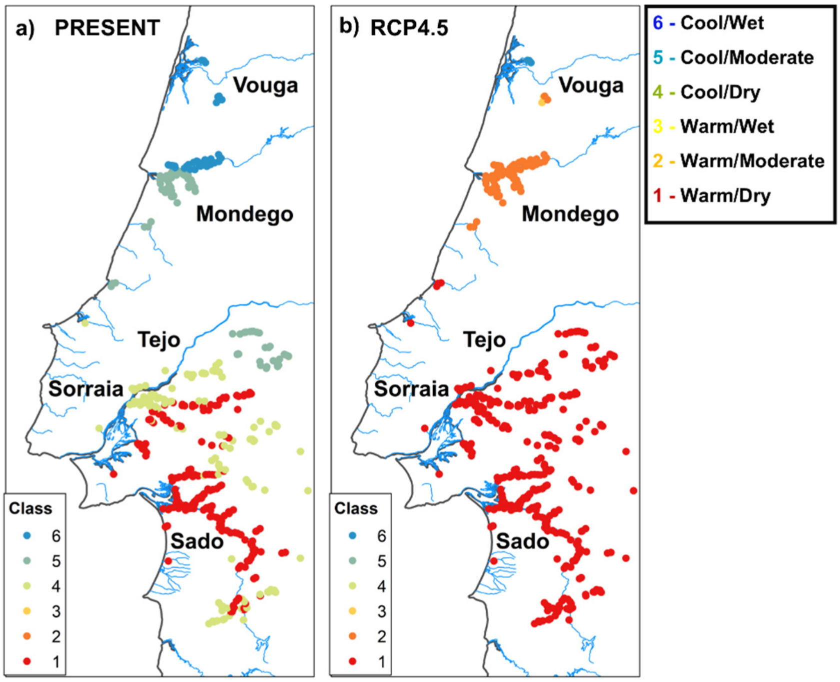

Figure 6. Distribution of the six classes of the Combined Index (CombI) over the Portuguese rice fields, for the (**a**) recent past (1950–2000) and for the (**b**) future period (2041–2060) under RCP4.5.

4. Discussion

Rice is a historically important crop in Portugal, which is produced and largely consumed nationally. In the present study, a high spatial resolution bioclimatic characterization over the main rice producing regions in Portugal was performed. This zoning was achieved using several bioclimatic indices and an innovative combined index that takes into account the annual mean temperature and annual precipitation as main climatic factors. The new CombI also provides an easier and more practical integration with high resolution climatic datasets, which enables mapping the impacts of climate change. The indices are based on a very high resolution dataset (WorldClim Project) for a baseline period (1950–2000) and for four scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) within a future period (2041–2060). Climate change projections are carried out by using a 11-member GCM ensemble. This data was previously downscaled to a near 1 km grid spacing, allowing a thorough characterization of meso-climatic influences in rice production. The model and scenario uncertainties were taken into account and quantified.

Current rice growing areas are not only determined by climate, but also by historic factors, soil characteristics, land-use limitations, and environmental politics. Despite the importance of all these factors, the very high resolution spatial representation of the bioclimatic indices provided herein represent an important tool for better understanding rice bioclimatic growing conditions in Portugal. Under recent-past climates there is a clear gradient of heat and water stress from north to south (Figure 2). The Tejo and Sado rice growing areas present higher temperatures and lower precipitation than Mondego and Vouga. The summertime and wintertime conditions follow similar patterns to the annual features. Additionally, there is a coastal-inland effect due to the Atlantic Ocean influence. This effect is clearer in the seasonality indices and in Tcool and Pdry.

Under anthropogenic climate change, the Portuguese rice fields are projected to undergo remarkable changes that can represent important challenges to this sector. All indices point to annual higher temperatures and lower precipitations across all rice producing regions with strengthened seasonality. Furthermore, the rise of summertime temperatures (Twarm) may substantially increase water demands, which, when unmitigated, may bring physiological issues. Other weather extremes (e.g., hailstorms and late frosts) can also play a key role but are not taken into account herein. All these changes can ultimately result in negative impacts on this crop. Future shifts in the CombI to dryer and hotter classes, which are in close agreement with recent studies worldwide, provide evidence for increased temperatures and decreased precipitations in many rice-producing regions [40]. Future CombI spatial characteristics may imply a lower diversity of bioclimatic categories, resulting in a more homogeneous warm and dry climate throughout the country (mostly CombI 1 and 2). This is particularly true for the regions of Sado and Tejo, where CombI class 1 (warm/dry) future climate may threaten the rice productivity. In fact, the combined effect of increased warming and drying may cause damaging stress to rice on several physiological levels [41].

The projected increase in temperature, and consequently less cold days and more hot days, may have serious implications for rice production [40,41], particularly for the types of varieties that are currently grown in the country. Higher temperatures will result not only in reducing the growth duration of the rice crop, but also the duration of the grain filling stage, resulting in lower yield and lower quality rice grain [40]. The current varieties growing in Portugal are perfectly adapted to the current temperature conditions, and higher temperatures could lead to the loss of suitability of these varieties. Moreover, changes in precipitation may also exert a strong impact on rice production, with less water available for the plant. It is important to note that not all of the projected climate change impacts are negative, as the expected CO_2 rise may benefit this crop by increasing photosynthesis and biomass [41]. Figueiredo et al. [42] states that the combined increase of atmospheric CO_2 will partially compensate for the negative effect of temperature rise.

Given the results in the current study, an adequate and timely planning of suitable adaptation measures needs to be adopted by the rice sector. Wassmann et al. [40] suggests that possible adaptation options for heat stress may come from previous knowledge in regions that are already exposed to very high temperatures, such as in Iran and Australia. Varieties grown in these regions, which are more suitable for warmer climates, could indeed be an answer to this problem. Hence research on new/more adapted varieties that are more resilient against the future warming and drying represents a crucial component in future climate adaptation [40,41,43]. Another adaptation measure is to anticipate seeding timings in order to avoid the warmer periods [44]. Farmers can adapt to climate change to some degree by shifting planting dates, choosing varieties with different growth duration, or changing crop rotations. Drought stress is also expected to aggravate through climate change and the synergetic effect of increased warming and dryness should strongly impact rice production [45]. Irrigation systems are to some extent shielded from immediate drought effects [22]. The buffer effect of irrigation against climate change impacts, however, will depend on the nature and state of the respective irrigation system. Additionally, in Portugal, water resources for agriculture are scarce, and water competition, either for other sectors or for human consumption is very high. As such, water saving techniques in irrigation should also be researched. Further, the use of more drought tolerant varieties may indeed be crucial for the sustainability of this crop in future climates [18,46]. Technological progress may also be an important tool to cope with the negative impacts of future climates, but alone, it is viewed as insufficient to cope with climate change [40].

It is important to recognize that climate change adaptation strategies need to incorporate several actors from the rice sector, such as farm-level implementations and national-level policies and investments [40]. By depicting bioclimatic conditions at a very high resolution, for both current and future climates in Portugal, along with advances in understanding the optimal requirements of the traditionally grown or autochthonous rice varieties, a better understanding of adaptation strategies to climate change impacts can be fostered within this important agrarian sector.

5. Conclusions

We conclude that climate change may negatively impact the viability of rice production in Portugal, particularly taking into account the national grown varieties. Focus should be given to the adequate and timely planning of suitable adaptation measures, which may become crucial to ensure the sustainability of this historically important food sector in Portugal.

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