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The Bioclimatic Change of the Agricultural and Natural Areas of the Adriatic Coastal Countries

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Abstract: In this study, the present bioclimatic conditions and the estimated changes of the bioclimate over natural and agricultural areas of the Adriatic territory (Albania, Bosnia and Herzegovina, Croatia, Italy, Montenegro, and Slovenia) are analysed and presented. For this purpose, a survey on De Martonne's bioclimate categories' spatial distribution over the entire examined area and individual countries is conducted for the reference period (1981–2010) and for three more future time periods (2011–2040; 2041–2070; 2071–2100) under two emissions scenarios (ssp370/RCP7 and ssp585/RCP8.5). The very high spatial resolution (~300 m) results demonstrate that the potential future alterations of the Adriatic territory's bioclimate indicate the probable acceleration of the trend towards warmer and dryer conditions by 2100 under the RCP8.5 scenario, with the Italian region's agricultural areas mainly being influenced. Moreover, as the studied scenarios project, the bioclimatic impact will affect natural and agricultural areas. For the agricultural areas, the semi-dry class (the most xerothermic in the study area) will expand from 4.9% (reference period) to 17.7% according to the RCP8.5 scenario for the period 2071–2100. When over the natural areas, the related variation of the same class is from 0.9% to 5.6%. In general, the western part of the Adriatic coastline is more vulnerable to climate results than the eastern one.

Keywords: climate change; bioclimate classification; De Martonne index; aridisation; Italy; Albania; Bosnia and Herzegovina; Croatia; Italy; Montenegro; Slovenia

Citation: Charalampopoulos, I.; Droulia, F.; Evans, J. The Bioclimatic Change of the Agricultural and Natural Areas of the Adriatic Coastal Countries. *Sustainability* **2023**, *15*, 4867. https://doi.org/10.3390/su15064867

Academic Editors: Teresa Patricia Feria-Arroyo, Engil Pereira and Georgios Koubouris

Received: 19 January 2023
Revised: 22 February 2023
Accepted: 7 March 2023
Published: 9 March 2023

1. Introduction

The undeniable rapid development and threatening nature of climate change (CC) have designated this spatiotemporal phenomenon as the topic of major scientific concern in recent decades [1]. Thus, CC may be characterised as the epicenter of contemporary global scientific research focused on the changes in the bioclimate or bioclimatic change.

The Adriatic territory (ADT), consisting of 6 coastal countries (Albania: AL, Bosnia and Herzegovina: BA, Croatia: HR, Italy: IT, Montenegro: ME, Slovenia: SI), constitutes an extensive and diversified European region which is expected to experience strong pressure due to climate change (CC) [2,3]. Projections by the end of the 21st century under the A1B emissions scenario reveal air temperature warming in the ADT (in relation to the 1961–1990 reference period), with ensemble minimum, mean, and maximum increases, respectively, of 1.78, 2.84, and 3.55 °C during winter; and of 3.10, 4.31, and 5.39 °C during summer. On the contrary, precipitation in the ADT by 2100 is expected to decrease, with values ranging from −59.45 to −4.57 mm per winter season and from −60.61 to −12.78 mm per summer season [4]. Projections on the future temperature regime of the western Balkans (which, among other countries, also include AL, BA, and ME) report an average increase of 2.0 °C and 4.4 °C according to the RCP4.5 and RCP8.5 emissions scenarios, respectively, by the end of the century. Aridisation trends are foreseen given the expected pronounced decrease in the precipitation amount by 20–30% during summer, accompanied by the increase of the dry days' incidents by 20%. By contrast, a higher frequency of spring floods is also projected for the future, owing to the predicted increased winter rainfall amounts [5,6]. The observed and projected CC encompasses a more extensive ensemble of climate trends involving alterations of the extreme weather events' regime (e.g., of heat waves, heavy precipitation events, and drought incidents) characterised by increased frequency and intensity [3,7–9].

In conjunction with the documented temperature increases and precipitation reductions, the climate projections for the ADT emphasise the territory's vulnerability to CC, with direct influences on its abundant natural ecosystems and agricultural areas [10–13]. The changing climate's both present and projected future impacts on natural areas may include, among others, increased water stress [14], increased aridity and high vulnerability to soil degradation [15], the growth rate depletion of forest trees [16], the high susceptibility to tree vitality loss [17] and increased tree mortality [18], the elevated risk of fire initiation [19], the reduction of biodiversity [20], and the increased frequency of alien plant invasions in natural habitats [21].

The environmental conditions also represent indispensable factors for agriculture, given the mounting evidence that CC has already strongly modified agricultural crop production systems [1,22,23]. The up to the present and future impacts involve greater influences on crop evapotranspiration [24], the increased risk of heat-caused plant injuries [25], the decline of crop quality production and the reduction of crop yields [3,26,27], higher yield variability, the reduction of suitable areas for the cultivation of traditional crops [28,29], and the further (northward) expansion of cultivations to areas which were previously constrained by the prevailing unsuitable environmental conditions (e.g., increased temperature and frequent droughts) [3,12,25,27,30]. Even though individually, temperature and precipitation are valuable atmospheric elements in investigating CC, the overall apprehension and magnitude of CC in bioclimatic terms is expressed more comprehensively by the bioclimatic indices/indicators [31]. The bioclimatic indices reflect formulas that comprise mathematical combinations of climatic parameters, the values of which are derived from meteorological measurements [32]. These formulas calculate the values of climatic factors and conditions that positively or negatively impact vegetation (or other biological factors) and which may also correlate with the main prevailing vegetation types [33]. Bioclimate indices, in general, have been widely exploited in Climatology, Bioclimatology, and agricultural studies [24,29,34–37] for the achievement of multiple objectives, thus demonstrating their major significance as tools for the characterisation of climate types.

Nearly one century ago, the French climatologist De Martonne proposed the homonymous bioclimatic index (De Martonne bioclimatic index: IDM) to estimate the degree of dryness of a given region's climate by classifying it into six classes, from "dry" to "extremely humid", through the correlation of precipitation and air temperature [24]. Although the IDM is one of the oldest aridity–humidity indices, its efficiency, accuracy, and relevance to the arid–humid climate categorisation prove its utility, make it widely applicable [34,38,39] for climate classification, and demonstrate its common incorporation in climatological, agricultural and land or water resources management investigations [24,32,40].

For the Italian Peninsula (Emilia–Romagna region), Nistor and Mîndrescu [38] have demonstrated significant decreases in the IDM index during the past (1961–1990), present (2011–2040), and future (2041–2070) examined periods, suggesting the aridisation of the studied area in the northern, eastern, and central sides, where the sub-humid and Mediterranean climates were identified. More specifically, the semi-humid class has been expanded from the period 1961–1990 to the period 2011–2040; and during the second period appeared the Mediterranean class. This phenomenon sprawled further in the third period (2041–2070). Passarella et al. [32], who utilised long-term data from 1931 to 2010, demonstrated the predominance of Mediterranean bioclimatic characteristics over the Apulia region (southeastern Italy) and highlighted the probability of irrigation needs in agriculture due to increasing xerothermicity. My et al. [41] have revealed that according to the estimated IDM, all examined locations of the Apulia region have not experienced significant aridity trends over the 1956–2019 period. Coscarelli et al. [42] have reported trends toward more arid conditions in the Calabrian basin (southern Italy). At the same time, the results of Caloiero et al. [34] suggest that CC involving a marked increase of the sub-humid class may be responsible for the forest cover change in the same region for the period of 1916–2010. Lione et al. [43] have attributed the observed forest decline severity to shifting Piedmont's (northwestern Italy) climate to significantly marked xerothermal conditions estimated between 1994 and 2007 compared to 1951–1986, in which no decline was reported. Savo et al. [33] have also discussed the increased climate aridity resulting from the Tolfa-Cerite area (Rome prefecture, Central Italy) over the period from 1951 to 2007, which was demonstrated by the shifting of the climate from humid to sub-humid. The researchers highlighted the possible risk for the extrazonal forests that commonly develop at higher elevations and constitute distinctive elements of the local landscape, but also the negative impacts on agriculture due to the foreseen reduced groundwater recharge. Majstorović et al. [44] analysed climatic data spanning from 1894 to 2003 based on the IDM and concluded in Sarajevo's (Central-eastern Bosnia and Herzegovina) general aridisation trend, but also in the rapid increase of temperature and of IDM after comparison of the trends between the 1894–1993 and 1894–2003 periods. Zulum and Majstorović [45] have studied the aridity trends for the years 1951–2006 in Bosnia and Herzegovina and have demonstrated the unusually large number of moderate to extreme droughts occurring particularly in the last decade of the study period. Brđanin and Sedlak [46] have applied the IDM for the bioclimatic classification of the Lim valley (eastern Montenegro) between the years 2009 and 2018. The values of the index indicated very humid and extremely humid climates, with the highest values resulting from the winter season. A survey on a sub-continental level has been performed by Nistor [47] for the whole southeastern European territory during the present (2011–2040) and future (2041–2070) time periods, where the findings have indicated extremely high climate effects on groundwater resources due to aridisation in the Pannonian basin (including northeast Croatia and northeast Slovenia). In a study of similar spatial magnitude, Cheval et al. [39] have also reported significant shifts towards more arid categories in regions of southeastern Europe and specifically from the semi-humid regime occurring during 1961–1990 to the extension of the Mediterranean bioclimate by 2050 in the Pannonian Plain.

As demonstrated from the above, investigations involving the application of the IDM have documented aspects regarding the change of bioclimate, mainly during past and lesser during future periods, focusing predominantly at the local scale and less frequently at the country level; it becomes evident, however, that surveys on a sub-continental level appear to be very limited. Additionally, there is a considerable lack of projection investigations on the whole of the ADT or on individual country-level areas concerning their future bioclimate evolution. The survey also ascertained that the degree of the spatial resolution adopted in the studies is relatively coarse (e.g., from 25 km up to 1 km). Following intense reflection on the aforementioned, it was considered appropriate to investigate the spatiotemporal distribution's changes of the bioclimatic De Martonne bioclimatic index (IDM) that combines the two main climatic parameters (temperature and precipitation) in the ADT, a reasonably extensive territory that represents a mosaic of natural variations and of distinguished agricultural areas. The variability of the IDM is studied over a reference period (Ref: 1981–2010) and three time periods (p1: 2011–2040; p2: 2041–2070; p3: 2071–2100), computed at a high resolution of approximately 300 m under the RCP7 (ssp370) and RCP8.5 (ssp585) emissions scenarios. The differences between the present and the future bioclimate profile are being approached, with the aim of identifying short-term and long-term bioclimatic change trends.

The effort to predict the changes and future dynamics of many living organisms is considered paramount, even for human survival on Earth. In this concept, the relative effort involves natural habitats and crops of fundamental significance, given their high susceptibility to changes of bioclimate conditions, especially those related to temperature and precipitation.

The prime objective of this study is to calculate and analyse the spatial distribution of the IDM index in the selected area, which may be one of the most vulnerable in Europe to climate change. More analytically, the scope is the presentation of a very high-resolution IDM set of maps with the related spatial statistics on a country level, focused on natural and agricultural areas, according to two greenhouse gas emissions scenarios for three future periods. The novel features of the present study include the application of the IDM in a relatively extensive area represented by the entire ADT, focusing on the illustration of the present and projected bioclimate evolution in ADT and in its individual countries, by employing, for the first time, a high degree of spatial resolution (~300 m) for this purpose. Overall, the presented findings could be a basis for the decision-making processes related to crop production and natural area conservation at regional and country levels.

2. Materials and Methods

2.1. Study Area

As illustrated in the map (Figure 1), the agricultural areas dominate the Italian peninsula, presenting their vast expansion in the northern part of the country (in the peripheral area of the Po valley), and in the lowland areas adjacent to the sea and regions spanning on both sides of the natural areas of the Apennines. A wider expansion of the natural areas occurs at the northernmost border of the country, given the presence of the Italian Alps. Apart from a relatively small natural area occupation representing the Sicily Apennines, the remaining Sicily region is subjected to agricultural exploitation. In contrast, agricultural and natural areas appear to be almost evenly distributed across Corsica. The prevalence of natural areas is demonstrated for the eastern Adriatic zone, where sporadic limited agricultural activity occurs along the Adriatic coast, except for AL, where further inland rural activity is displayed. This is also the case for northeastern SI and HR, where rural areas are concentrated in the wide proximity of the Pannonian basin. In the case of HR, agricultural areas also occupy a substantial interior part of the country. BA's mostly mountainous profile is reflected by extensive natural landscapes and lesser agricultural activity intensified in the northernmost country's lowland zone. Small-scale agricultural activity is depicted for southern ME (over the Zeta plain), corresponding to the region's extensive mountainous terrain. The extended natural highland areas prevail in most parts of AL (e.g., Albanian Alps in the north, the Skanderbeg Mountains in the center, and the Pindus Mountains in the southeast), limiting agricultural development in the coastal zone plains and plateaus extending primarily in the west along the Albanian Adriatic Coast. Overall, the selected countries cover more than 470,000 km^2, including vast amounts of agricultural and natural areas.

2.2. Data and Methods

In general, the analytic process of this study is conducted based on the raster calculation of the widely applied De Martonne index for four time periods under two greenhouse gas emissions scenarios in an ultra-high spatial resolution. More specifically, the greenhouse emissions scenarios are the ssp370 (corresponding to RCP7) and the ssp585 (corresponding to RCP8.5), and the time periods are 1981–2010 as reference period (Ref), 2011–2040 (p1), 2041–2070 (p2) and 2071–2100 (p3). More specifically, the ssp370 is linked to the RCP7 scenario, representing a medium-high socioeconomic development path with radiation forcing, which peaks at 7.0 W/m^2 by 2100; and the ssp585 is linked to a high-intensive scenario, and the number of its emissions is the highest we investigate reaching 8.5 W/m^2 by 2100 (RCP8.5). The related RCP characterization means Representative Concentration Pathways with the corresponding radiation forcing number [48,49]. This study uses the RCP symbolization since it is more common in associated studies.

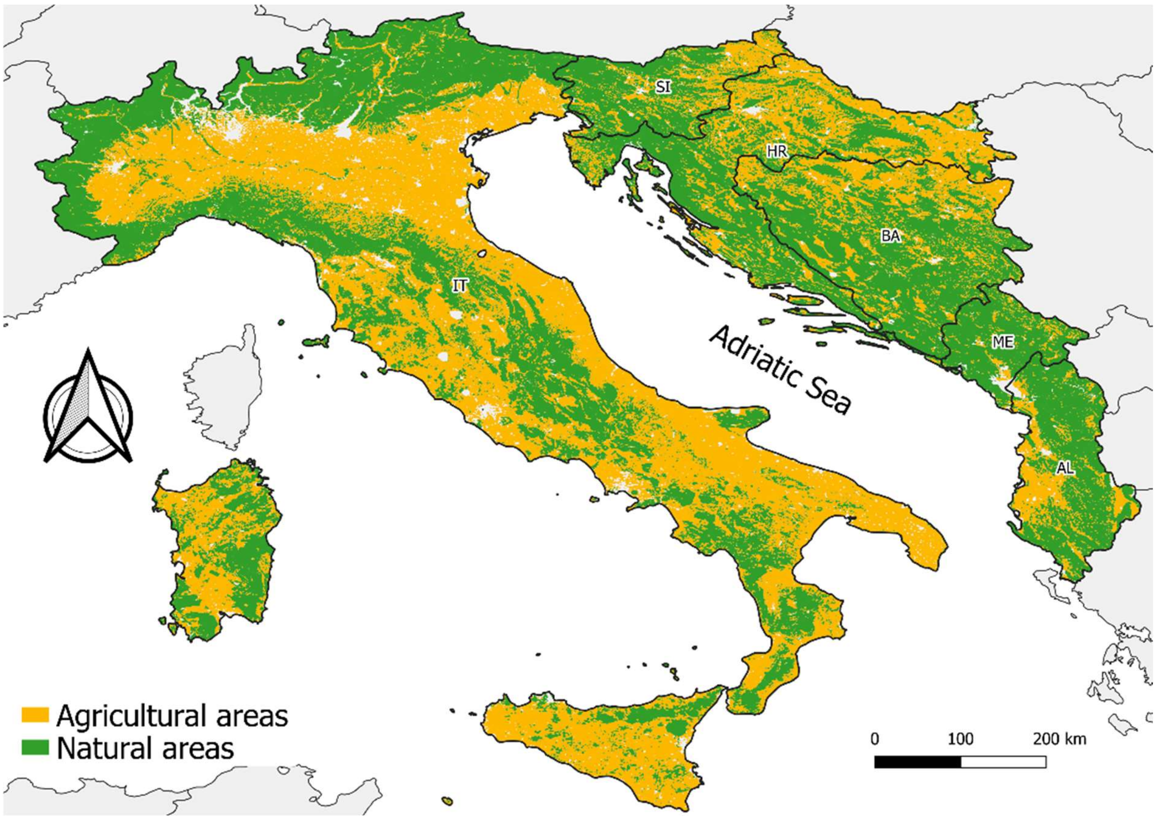

Figure 1. The study area with the generalised Corine Land Cover 2018 categories (AL = Albania, ME = Montenegro, BA = Bosnia and Herzegovina, HR = Croatia, SI = Slovenia).

Atmospheric data and Analysis

The major dataset employed for the present study originates from the CHELSA repository [47,48], a well-documented and widely utilised dataset by the academic and research community [50–54]. It contains a variety of atmospheric indices and indicators along with fundamental parameters such as precipitation and air temperature in a spatial resolution of 30 arcsecs (~1 km). The CHELSA available data corresponding to a time period from 1979 to 2100 was carried out from reanalysis and climate change projection procedures.

The De Martonne index (IDM) is calculated using the annual average values of precipitation (P) and temperature (T) according to the following formula [36,55]:

$$\mathrm{IDM} = \frac{\mathrm{P}}{\mathrm{T} + 10}$$

where:

P: is the annual average precipitation (mm);
T: is the annual average air temperature (°C); and
10: is the coefficient employed to acquire positive values

Higher IDM values indicate humid climatic conditions, while lower values indicate drier climatic conditions (or xerothermic conditions). The index can be calculated at annual, seasonal, and monthly time scales. For this study, the annual calculation has been selected. The degrees of humidity or aridity in relation to the values of the IDM are exhibited in the classification scheme of Table 1, where a total of seven types of aridity classes are distinguished, accompanied by the respective descriptions of irrigation demands.

The downscaling of the CHELSA data to 300 m resolution was implemented by the robust regression process via the spatialEco [56] along with the Tidyverse [57] and Terra [58] R packages. The temperature data has been downscaled using the parameters of altitude, latitude, and the Euclidean distance from the shoreline, providing very high accuracy when the precipitation data have been resampled to the desired resolution via the bilinear method. Raster algebra procedures performed the IDM estimation for the selected scenarios and time periods.

The widely used CORINE Land Cover (CLC) dataset [59] has been utilised to separate the agricultural and natural regions of the study area. More specifically, in the year 2018, the CLC classes of 2.1, 2.2, 2.3, and 2.4 were unified as agricultural areas, and 3.1, 3.2, and 3.3 as natural areas. The accuracy of the CLC is better than 100 m with a thematic accuracy of ≥85%. Thus, having the land cover and its country borders polygons, the spatial statistical analysis was conducted to produce comprehensive plots and maps to monitor the qualitative and quantitative evolution of the bioclimatic change over the Adriatic Sea. The conducted analysis scheme is illustrated in Figure 2. The whole spatial and bioclimatic data handling and the related calculations were conducted using the R language scripts, and the mapping products were made by QGIS [60].

Table 1. The De Martonne Index (IDM) classification modified by Passarella et al. [32].

IDM Values	Types of Bioclimates	Description
IDM < 10	Arid or Dry	Needs continuous irrigation
10 ≤ IDM < 20	Semi-dry or Semi-arid	Needs irrigation
20 ≤ IDM < 24	Mediterranean	Needs supplementary irrigation
24 ≤ IDM < 28	Semi-humid	Needs supplementary irrigation
28 ≤ IDM < 35	Humid	Needs occasional irrigation
35 ≤ IDM ≤ 55	Very humid	Needs infrequent irrigation
IDM > 55	Extremely humid	Water self-sufficient

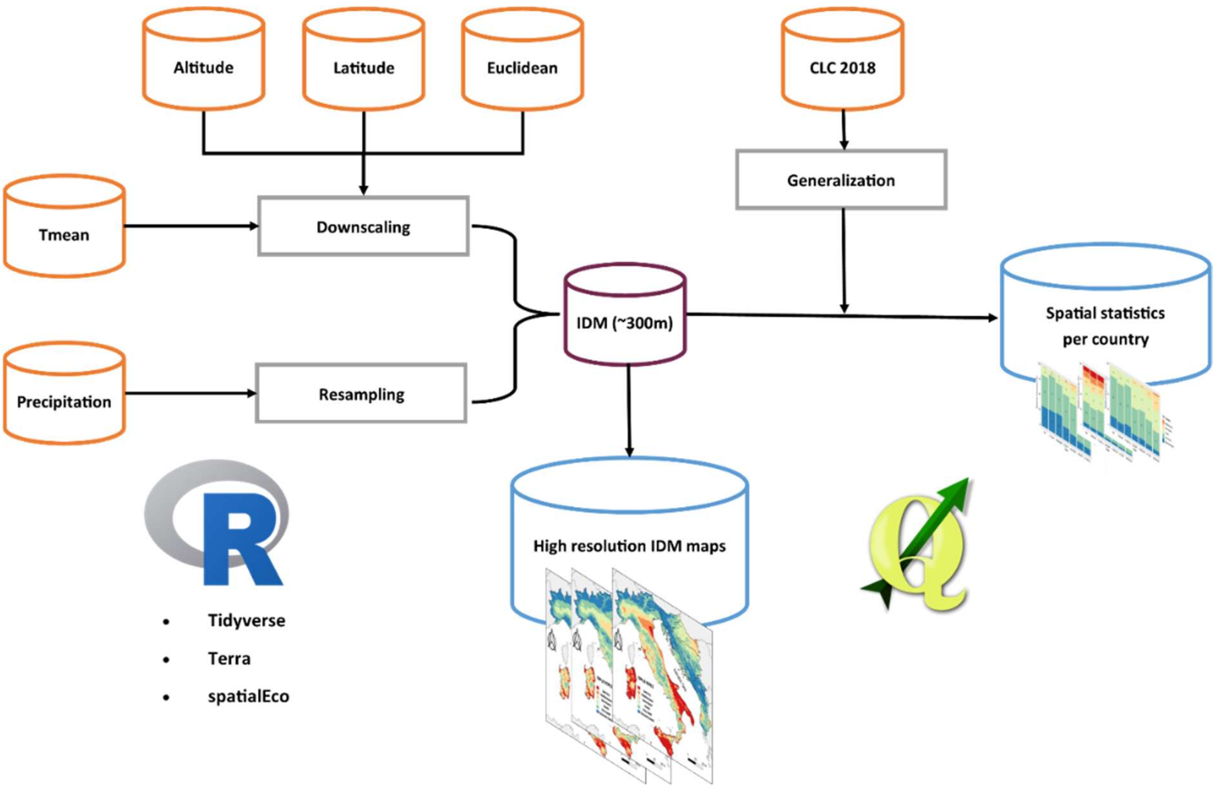

Figure 2. The flowchart of the conducted analysis process.

3. Results and Discussion

3.1. The De Martonne Index's Spatial Distribution

As depicted by the map (Figure 3) defining the IDM bioclimate zones at the reference period (1981–2000), the ADT is distributed among 6 De Martonne bioclimatic classes (semi-dry, mediterranean, semi-humid, humid, very humid, and extremely humid). The bioclimatic characterisations' scaling towards the more humid classes corresponds to the evolution of the terrain of the natural area towards higher altitudes. Thus, the more humid bioclimatic conditions represented by the very humid and extremely humid classes prevail in the (hilly or) semi-mountainous and mountainous regions of higher altitudes (e.g., natural areas of the Apennines and the Italian Alps) clearly dominating in the eastern ADT. Humid and semi-humid areas appear in lowland agricultural inland and coastal areas (e.g., in the Po valley surrounding area, along the central Italian Adriatic coast, in northern Sicily, in eastern HR, and a significant part of Sardinia). The dryer Mediterranean and semi-dry bioclimate types characterise agricultural lowland; mostly coastal areas (e.g., southeastern Italian Peninsula, central, western, and southern Sicily, and southern and eastern Sardinia).

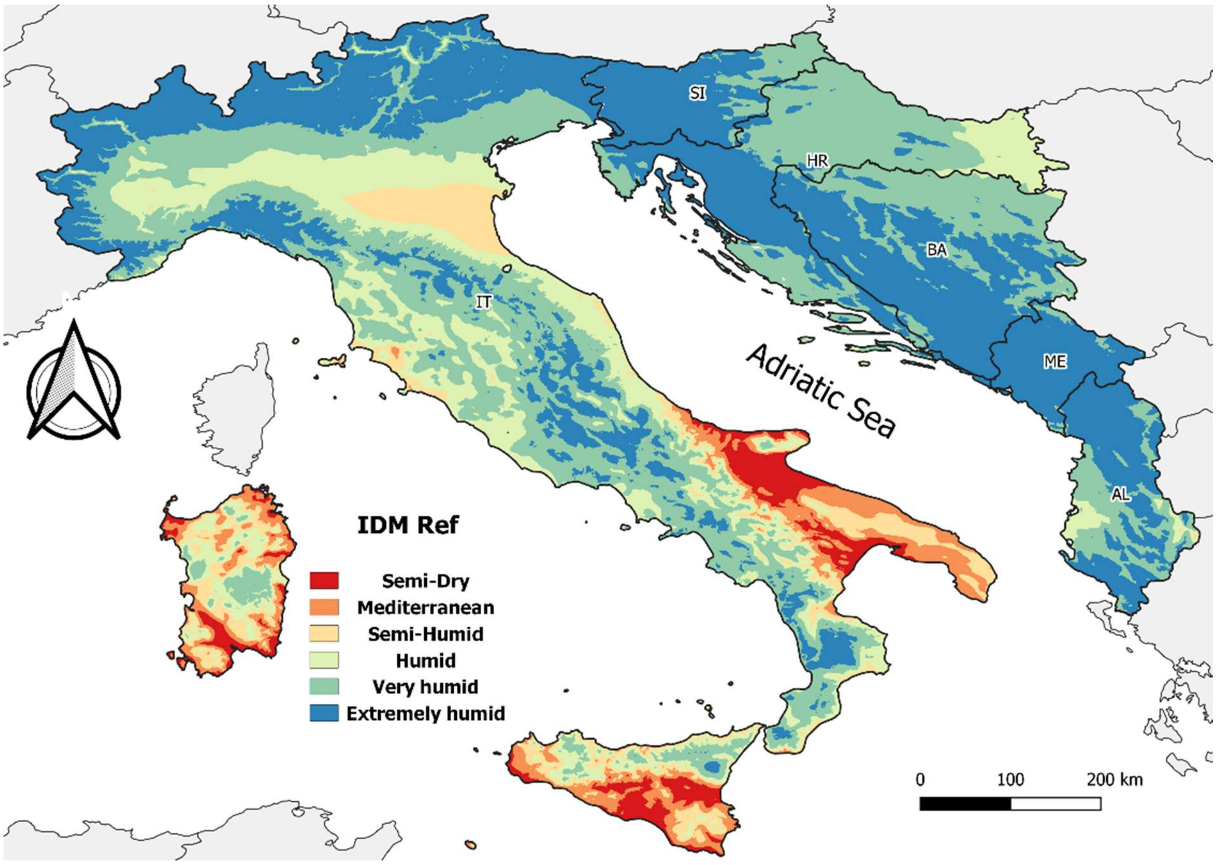

Figure 3. The De Martonne spatial distribution at the reference period (Ref) (1981–2010). IDM = De Martonne Index, AL = Albania, ME = Montenegro, BA = Bosnia and Herzegovina, HR = Croatia, SI = Slovenia.

For the 1st time period (2011–2040) under the RCP7 emissions scenario (Figure 4), projections reveal the bioclimate regime's distribution among the same 6 classes as the reference period. Concerning the latter period, a slight western expansion of the agricultural areas falling within the semi-humid class may be expected by 2040 in northern IT, at the expense of the humid class. In addition, there is a sprawl of very humid, in the place of the extremely humid class, in Albanian territory. A slightly more pronounced xerothermicity trend is depicted for the southeastern part of IT, where the Mediterranean conditions prevail in more extensive agricultural areas. Overall, the extremely humid conditions appear as more limited across the Peninsula, especially in its central natural landscape. Aridisation is more evident in Sardinia and is most intense in Sicily, where higher spatial distributions of the semi-dry conditions are projected to prevail mainly in agricultural areas. Results for the eastern ADT indicate almost similar distributions of the humid, very humid, and extremely humid categories with those depicted for the reference period. A slight differentiation is demonstrated for AL owing to the observed drying and warming trend (with the corresponding alterations in irrigation needs), where an expansion of the very humid regime at the expense of the extremely humid conditions is foreseen for both agricultural and natural areas.

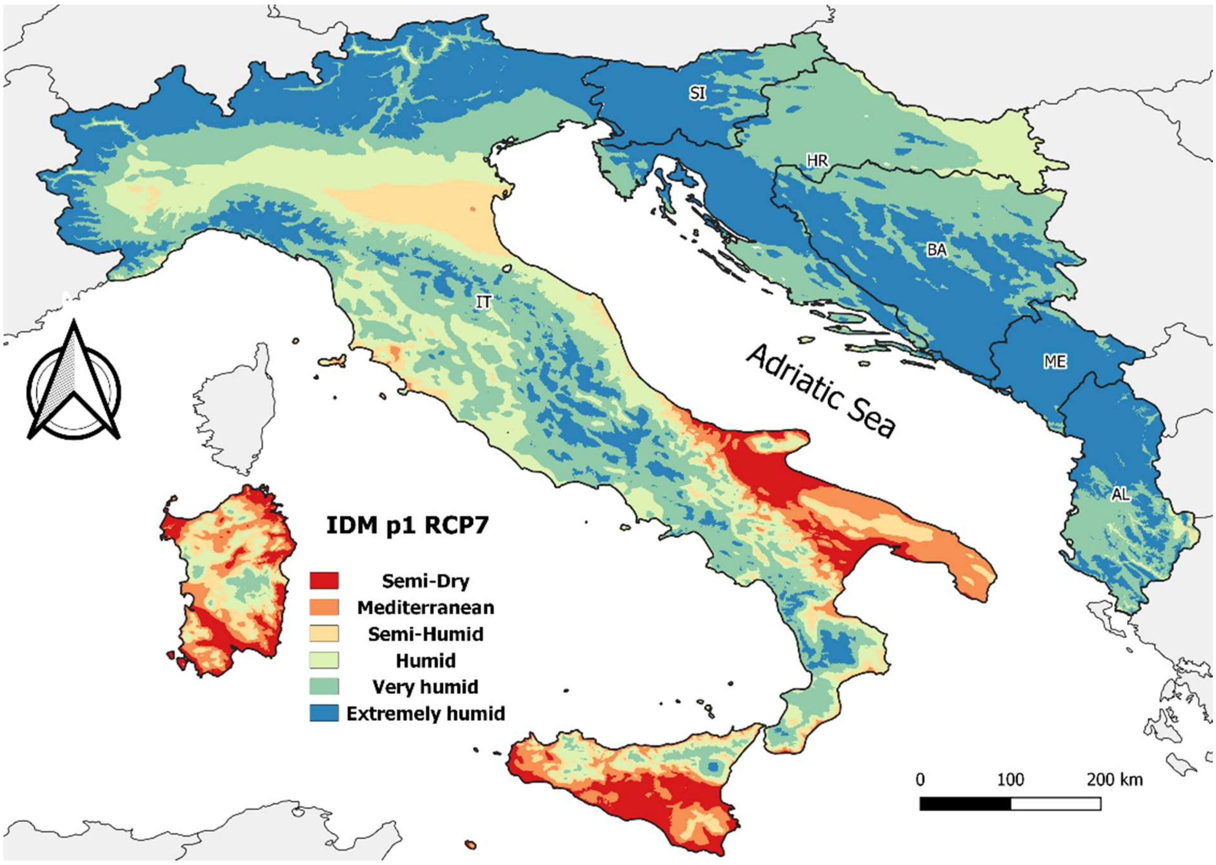

Figure 4. The De Martonne spatial distribution at the 2011–2040 (p1) RCP7 scenario. IDM = De Martonne Index, AL = Albania, ME = Montenegro, BA = Bosnia and Herzegovina, HR = Croatia, SI = Slovenia.

A profound xerothermic tendency is revealed for the 2nd time period (2041–2070) under the RCP7 emissions scenario (Figure 5). This becomes evident by the bioclimate's escalation to the Mediterranean class (and higher irrigation needs for the crops) in agricultural areas previously characterised by semi-humid conditions, as exhibited for the central coastal areas and the northeastern/southeastern parts of the Italian Peninsula. The substitution of the humid bioclimate also demonstrates this by the semi-humid characterisation (e.g., in the coastal and inner agricultural areas of central IT and eastern HR), by the more expanded humid agricultural areas evidenced in place of the very humid ones (e.g., northern HR, northern BA, and central eastern AL), and by the noticeable decrease in the extremely humid class's spatial distribution over the natural areas across central IT and eastern ADT. An even warmer and drier bioclimate is expected by 2070 for Sardinia and Sicily, given the further expansion of the agricultural areas with Mediterranean and semi-dry conditions, with the latter dominating a substantial part of Sicily.

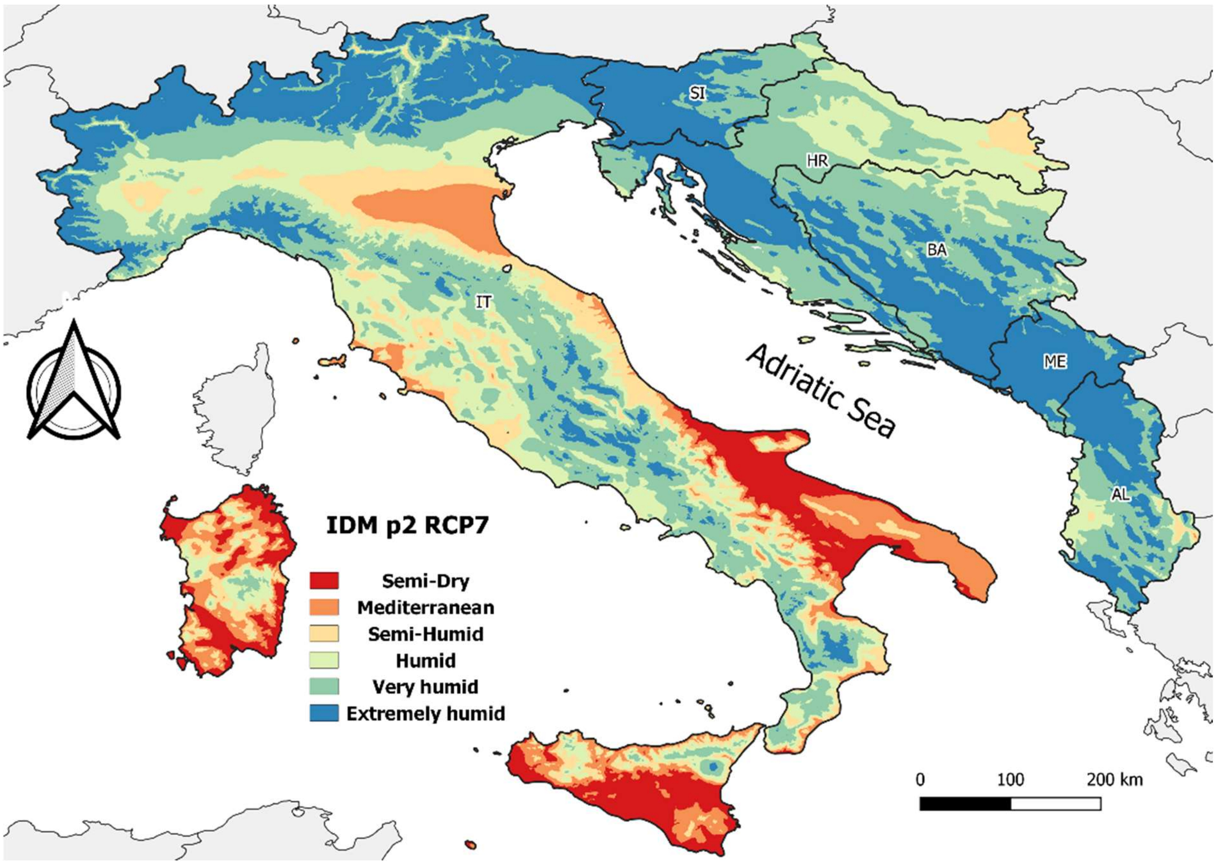

Figure 5. The De Martonne spatial distribution at the 2041–2070 (p2) RCP7 scenario. IDM = De Martonne Index, AL = Albania, ME = Montenegro, BA = Bosnia and Herzegovina, HR = Croatia, SI = Slovenia.

Projections for the long-term future time frame (2071–2100) under the RCP7 scenario highlight the ADT's bioclimatic regime change towards a more intense xerothermic bioclimate (Figure 6). The apparent future warmer and drier conditions affecting agricultural areas are demonstrated by the higher spanning of the Mediterranean category in place of the semi-humid category in northern, central coastal, and inland IT and eastern AL. More extensive rural areas are expected to be affected by the semi-humid bioclimate in northeastern HR and western AL, while significantly fewer natural areas across the central and southern Italian Peninsula are foreseen as extremely humid. A further limitation of the agricultural areas under Mediterranean conditions is predicted for the southeastern Italian Peninsula and Sicily, where the prevalence of the drier semi-dry regime is depicted. This is also the case for Sardinia, where both natural and agricultural areas are expected to face intense xerothermicity.

The bioclimates' spatial distribution for the 1st time period (2011–2040) under the extreme RCP8.5 emissions scenario (Figure 7) displays similarities to the respective period's distribution scheme resulting in the RCP7 (Figure 4). Regarding the latter scenario, the main differentiations for the RCP8.5 lie in the appearance of agricultural areas with a humid bioclimate, at the expense of the very humid conditions in western AL, and in the reduction of semi-humid agricultural areas in northwestern and central eastern IT. Contrarily, more extensive agricultural areas falling within the semi-humid category are illustrated for southeastern IT.

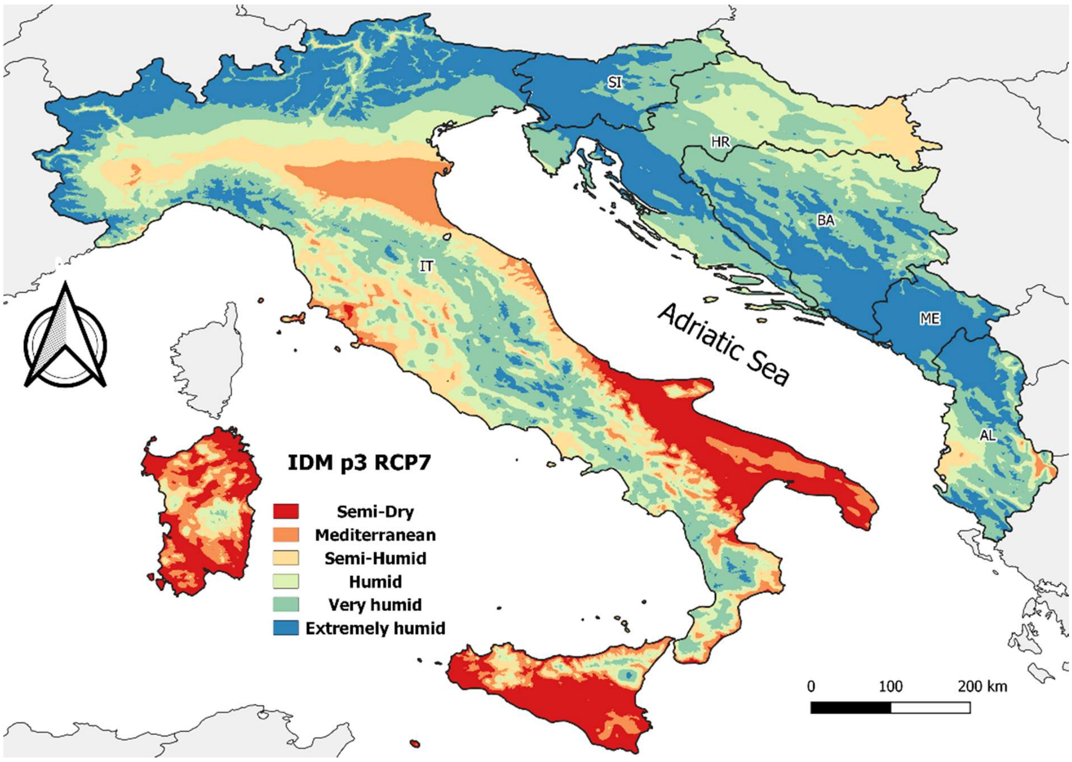

Figure 6. The De Martonne spatial distribution at the 2071–2100 (p3) RCP7 scenario. IDM = De Martonne Index, AL = Albania, ME = Montenegro, BA = Bosnia and Herzegovina, HR = Croatia, SI = Slovenia.

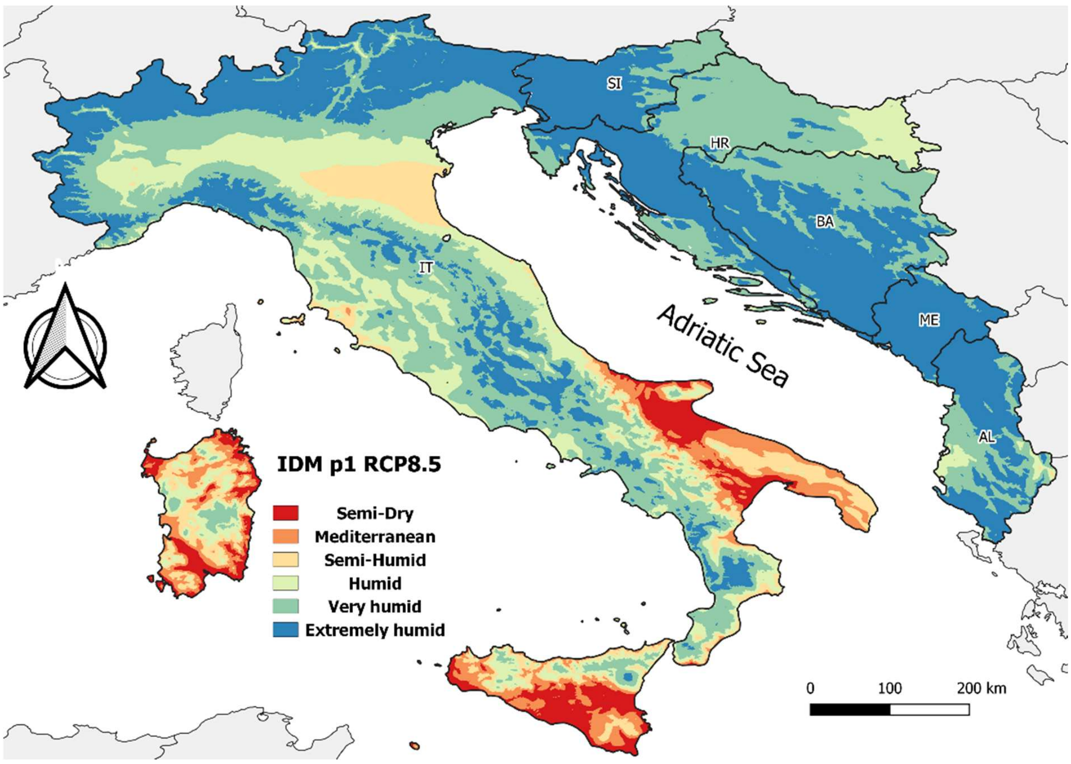

Figure 7. The De Martonne spatial distribution at the 2011–2040 (p1) RCP8.5 scenario. IDM = De Martonne Index, AL = Albania, ME = Montenegro, BA = Bosnia and Herzegovina, HR = Croatia, SI = Slovenia.

Projections for the 2nd period (2041–2070) under the RCP8.5 (Figure 8) depict the distribution of ADT′ s bioclimate regime among the same 6 De Martonne categories as in the previous cases. Although a practically similar distribution pattern is displayed compared with the respective RCP7 scenario (Figure 5), fewer extended agricultural areas with Mediterranean bioclimate characteristics appear in northern IT. Nevertheless, a slightly more pronounced aridisation trend is exhibited for Sicily, where the characterisation of more agricultural areas falling within the semi-dry category occurs. This slight xerothermic trend is also detectable for AL, where a few more agricultural areas of semi-humid and Mediterranean bioclimates appear in its western and eastern parts, respectively.

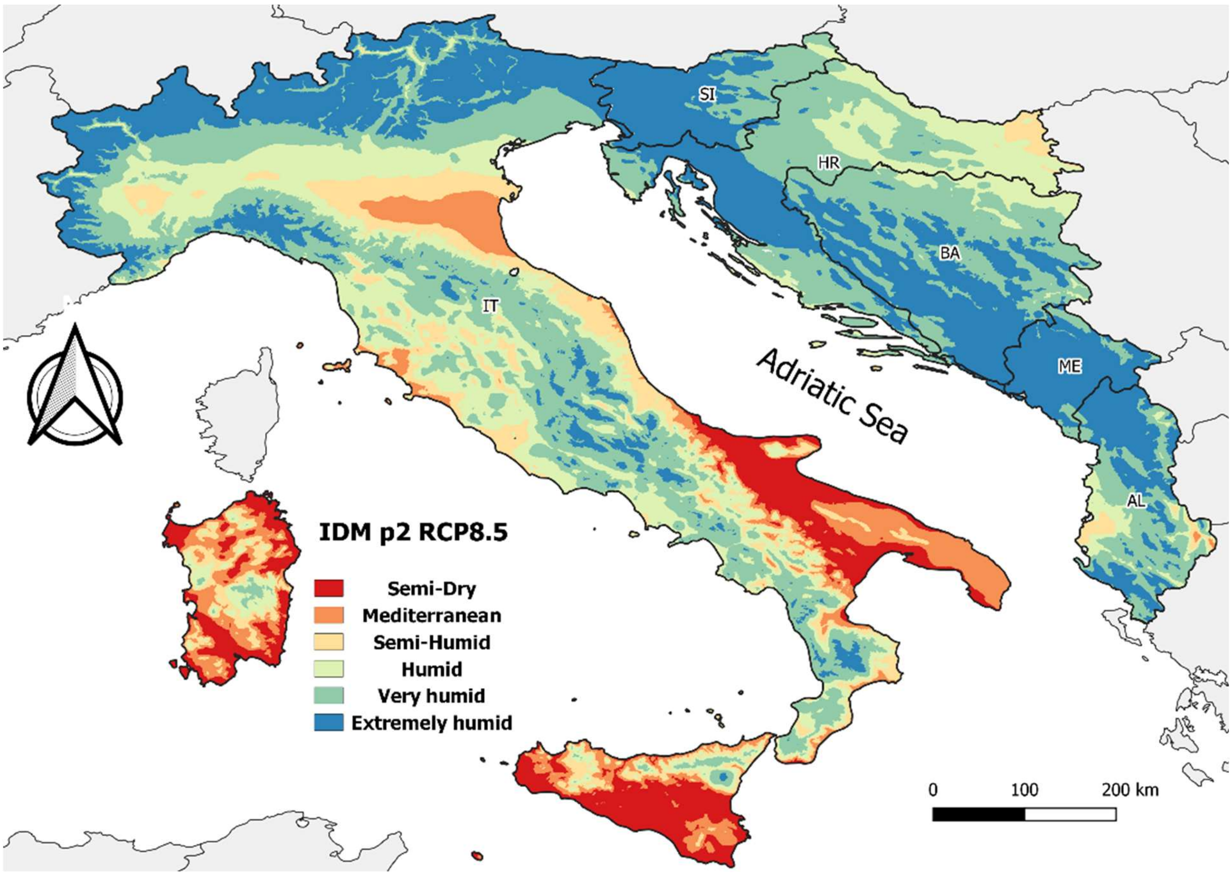

Figure 8. The De Martonne spatial distribution at the 2041–2070 (p2) RCP8.5 scenario. IDM = De Martonne Index, AL = Albania, ME = Montenegro, BA = Bosnia and Herzegovina, HR = Croatia, SI = Slovenia.

The spatial distribution of De Martonne's classes clearly demonstrates more intensified drying and warming of the ADT over the 3rd period (2071–2100) of the RCP8.5 scenario (Figure 9). In contrast with the results for the corresponding time frame of the RCP7 scenario (Figure 6), a section of the Mediterranean bioclimate zone is substituted with semi-dry conditions in the northern agricultural areas of IT. The semi-dry regime dominates, approximately, the entire southeastern part of the Peninsula. These intense xerothermic conditions are projected to impact the natural and agricultural areas of Sardinia and the rural areas of Sicily. An increased spatial distribution of the Mediterranean class is revealed for the Peninsula's coastal and continental agricultural areas. This trend towards warmer and drier conditions is also exhibited in the agricultural areas of northeastern HR, where an expansion of the semi-humid areas is depicted along the country's northern borders. This is also the case for western AL, where more semi-humid areas appear in the western rural part of the country. However, an approximately similar distribution pattern of the very humid and extremely humid bioclimate categories is projected over the ADT in accordance with the respective period of the RCP7 scenario.

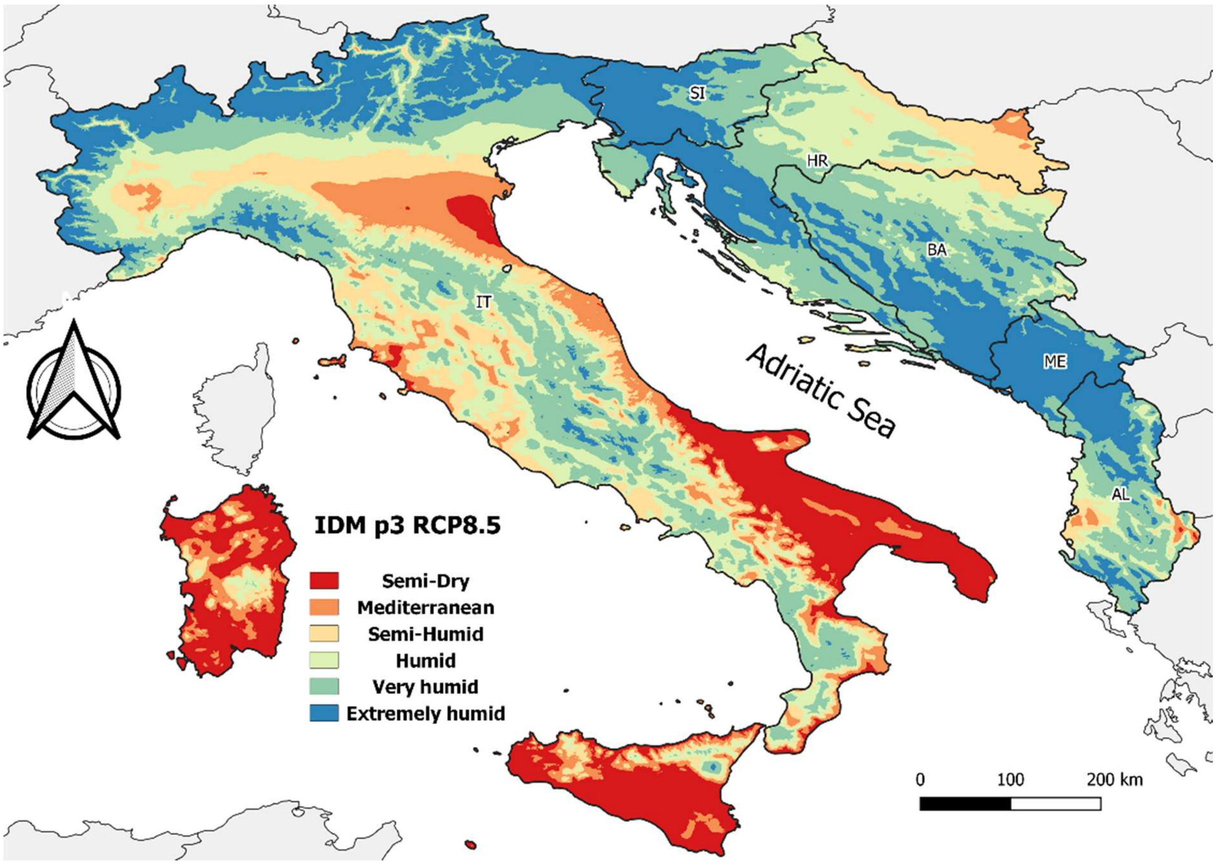

Figure 9. The De Martonne spatial distribution at the 2071–2100 (p3) RCP8.5 scenario. IDM = De Martonne Index, AL = Albania, ME = Montenegro, BA = Bosnia and Herzegovina, HR = Croatia, SI = Slovenia.

3.2. The De Martonne Classes' Spatial Frequency per Country

The relative frequencies of the bioclimatic classes resulting from the agricultural and natural areas of the individually examined countries (in alphabetical order: Albania, Bosnia and Herzegovina, Croatia, Italy, Montenegro, and Slovenia) are displayed in Figures 10–21. The reference period is designated as Ref. All investigated cases of the 1st, 2nd, and 3rd periods under the RCP7 scenario are designated as p1 RCP7, p2 RCP7, and p3 RCP7. Similarly, the respective cases under the RCP8.5 scenario are designated as p1 RCP8.5, p2 RCP8.5, and p3 RCP8.5.

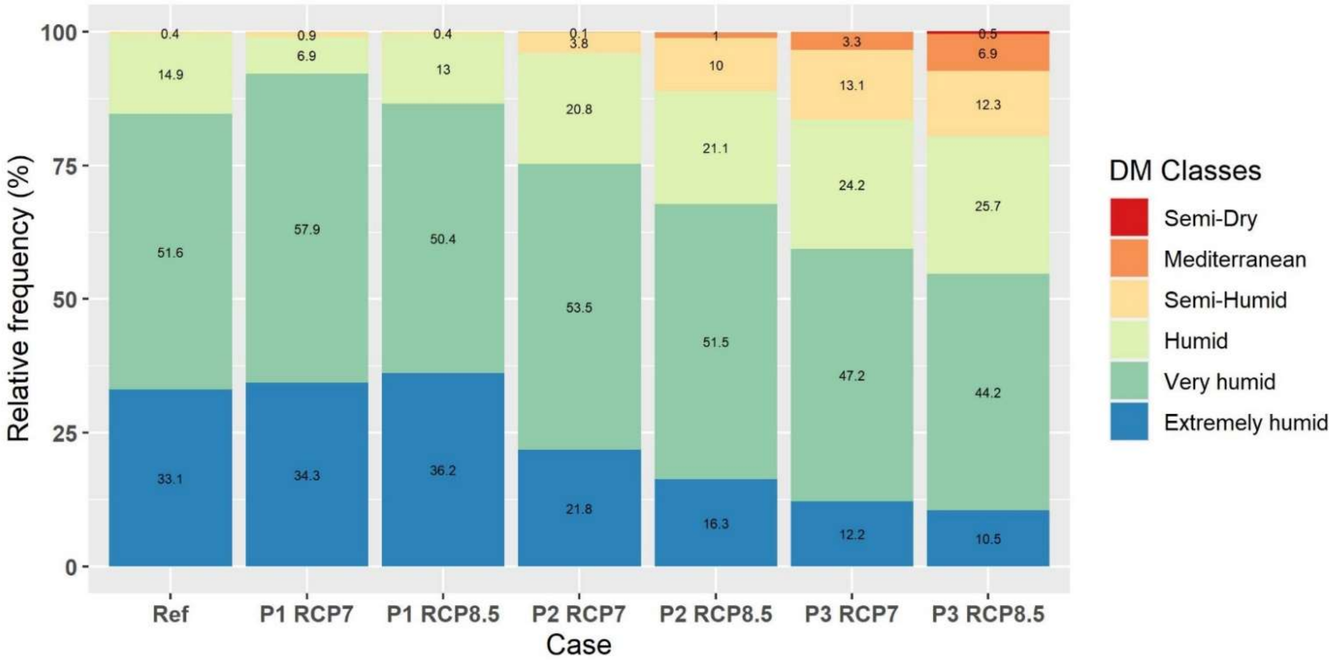

Figure 10. The relative frequency of the De Martonne classes over the agricultural areas of Albania.

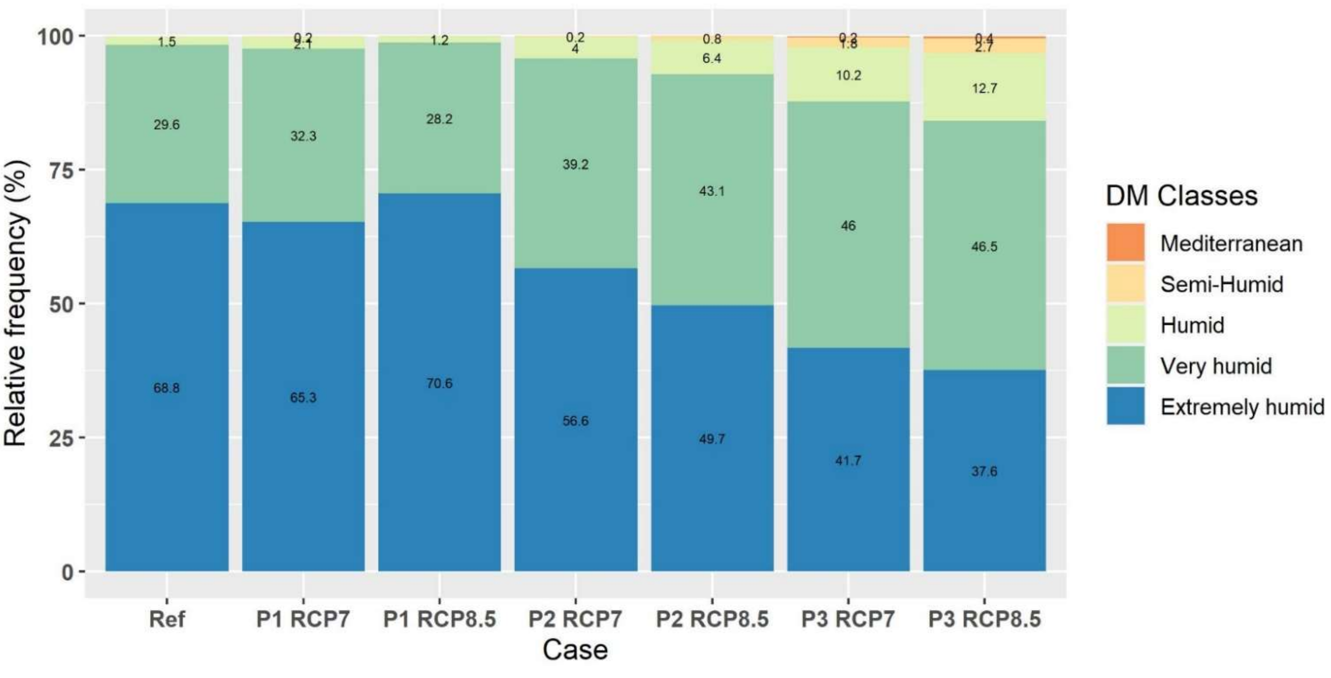

Figure 11. The relative frequency of the De Martonne classes over the natural areas of Albania.

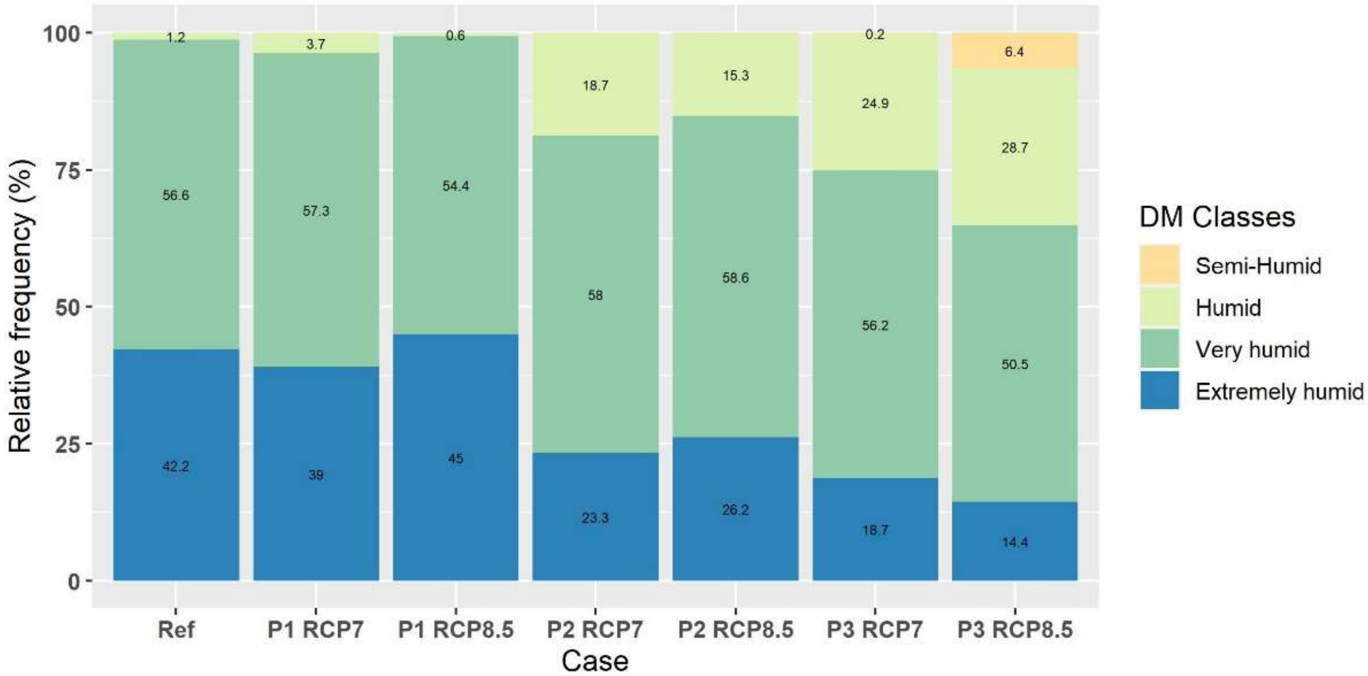

Figure 12. The relative frequency of the De Martonne classes over the agricultural areas of Bosnia and Herzegovina.

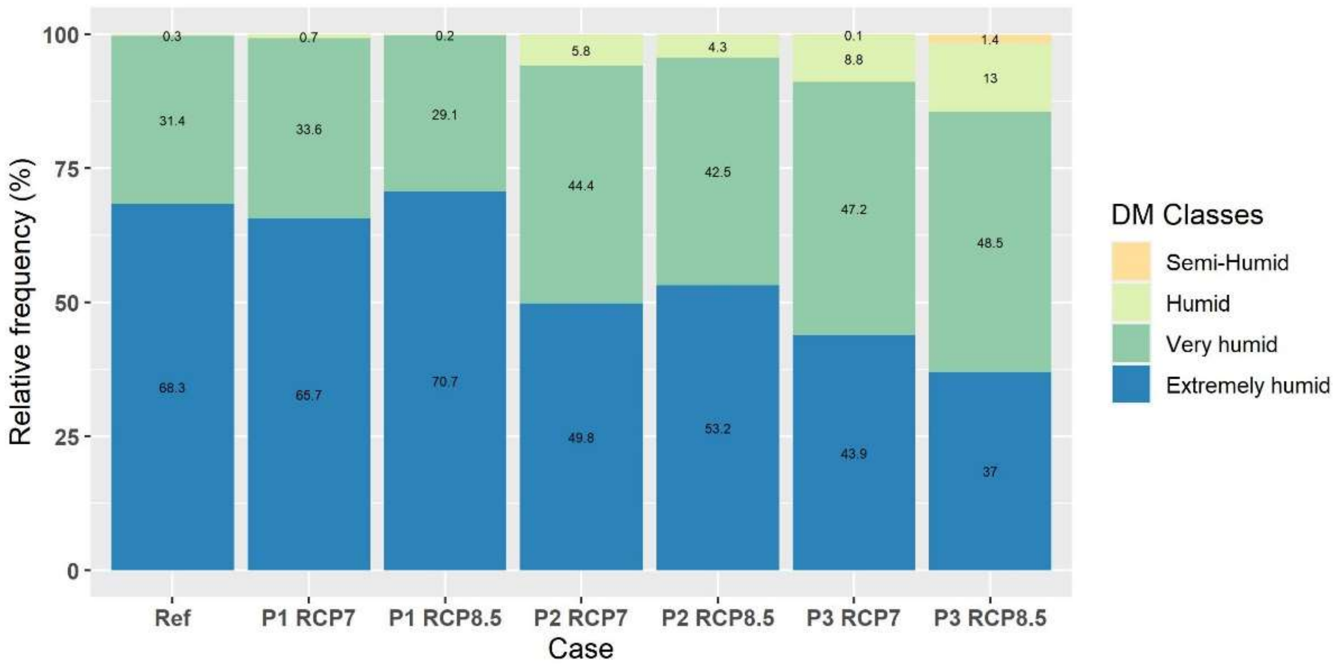

Figure 13. The relative frequency of the De Martonne classes over the natural areas of Bosnia and Herzegovina.

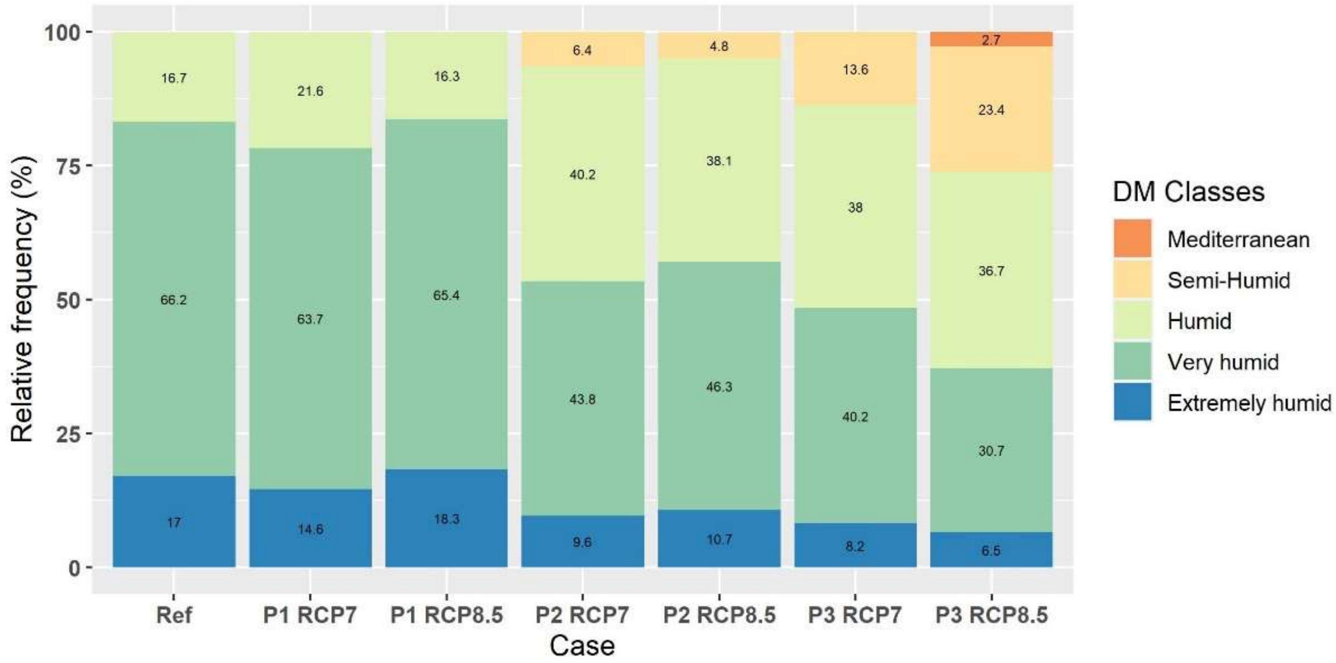

Figure 14. The relative frequency of the De Martonne classes over the agricultural areas of Croatia.

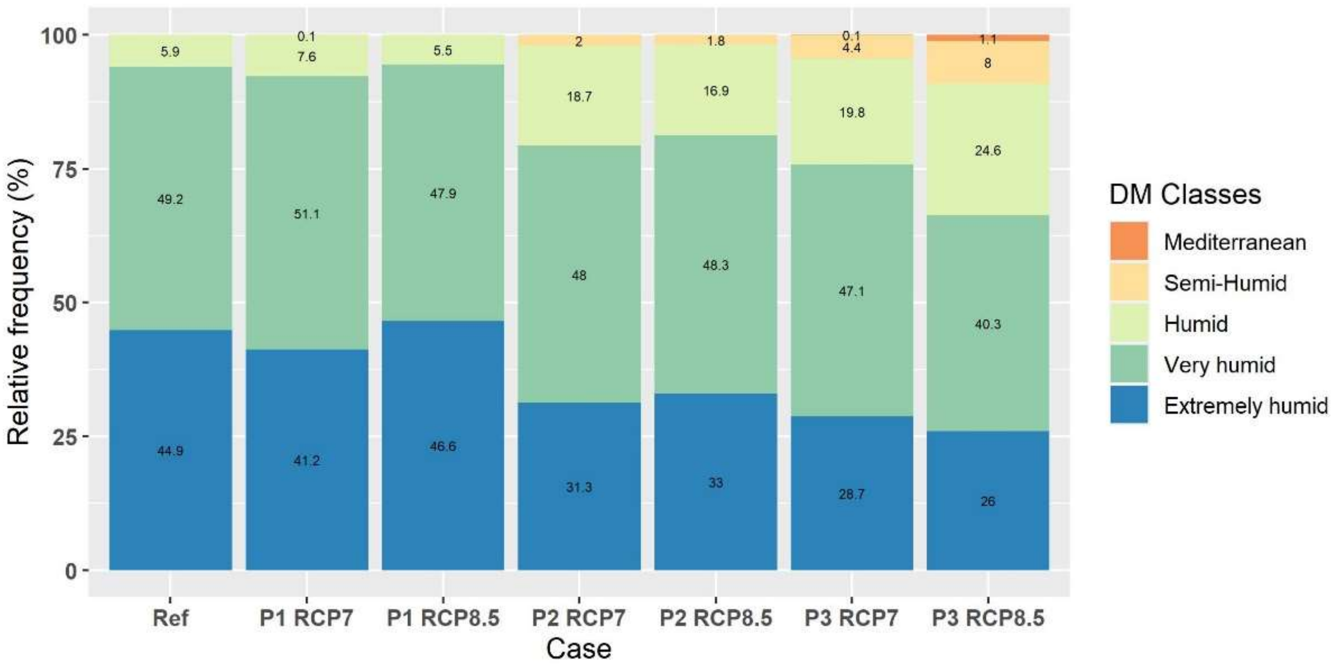

Figure 15. The relative frequency of De Martonne classes over the natural areas of Croatia.

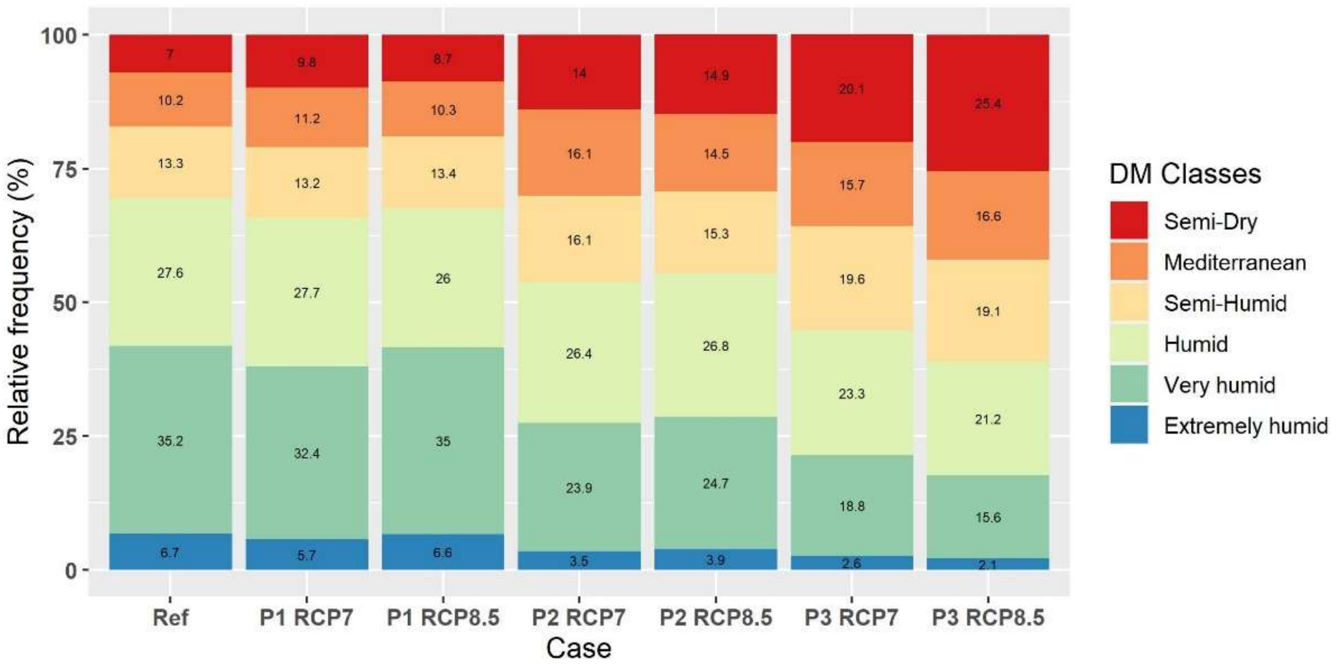

Figure 16. The relative frequency of the De Martonne classes over the agricultural areas of Italy.

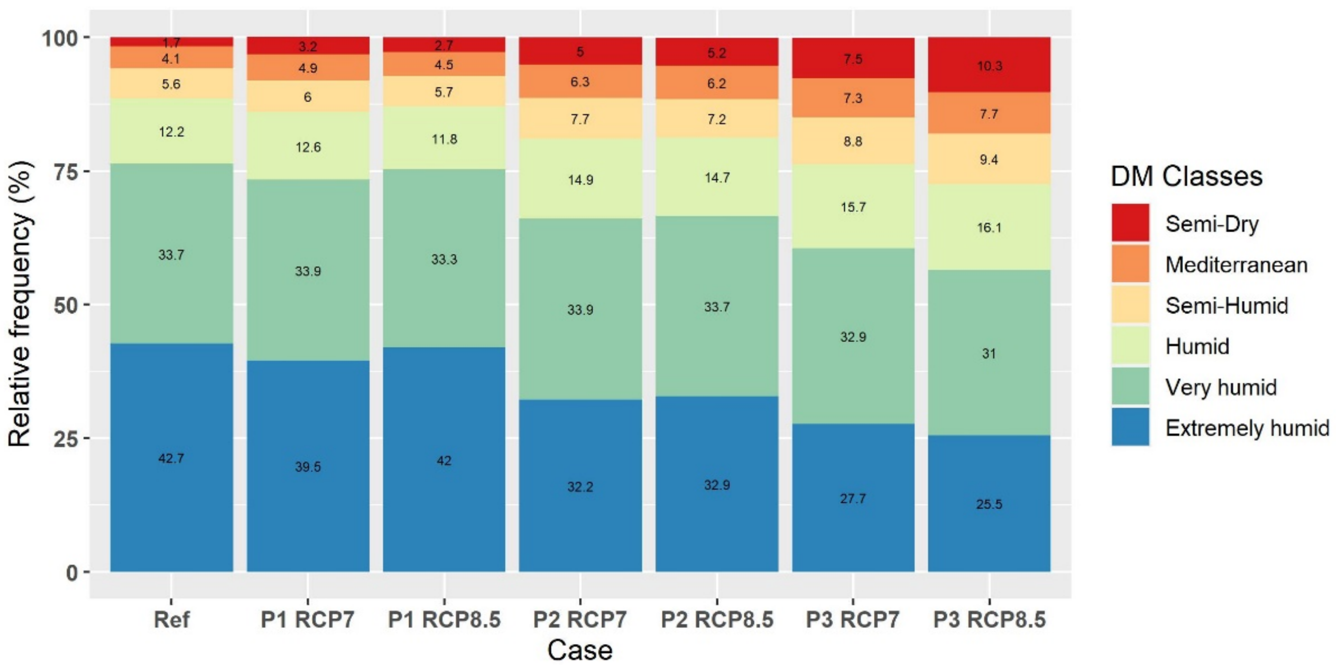

Figure 17. The relative frequency of the De Martonne classes over the natural areas of Italy.

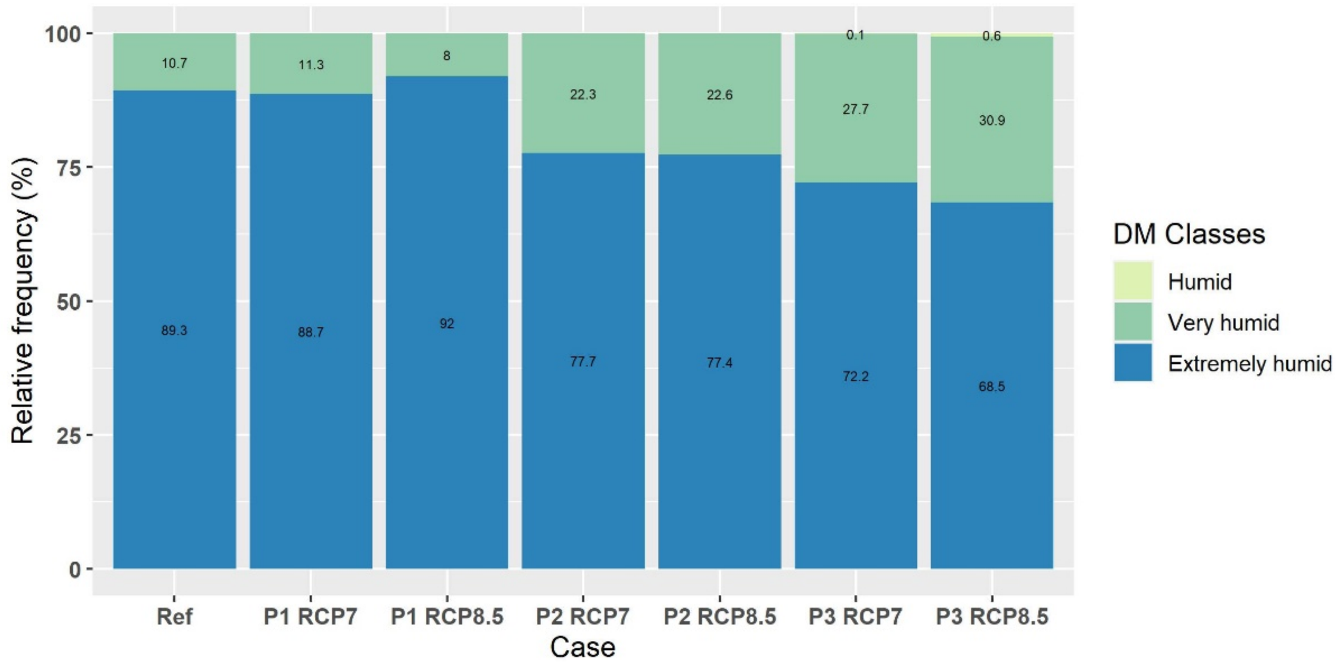

Figure 18. The relative frequency of the De Martonne classes over the agricultural areas of Montenegro.

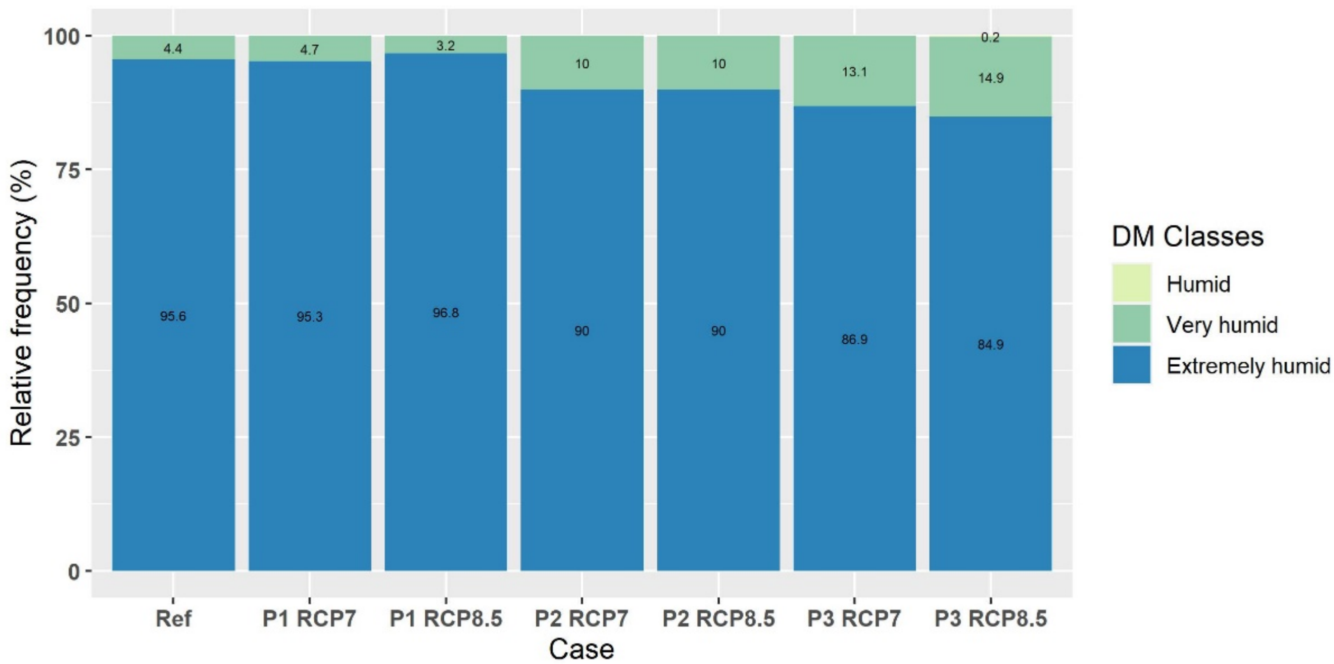

Figure 19. The relative frequency of the De Martonne classes over the natural areas of Montenegro.

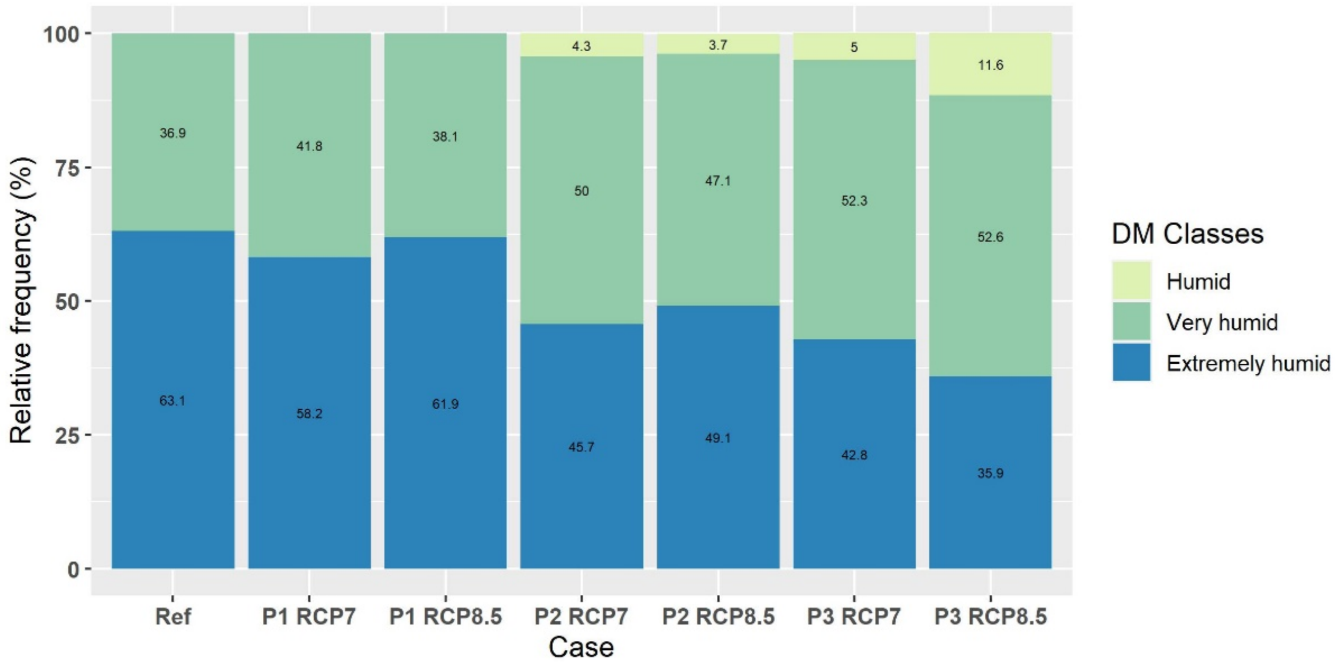

Figure 20. The relative frequency of the De Martonne classes over the agricultural areas of Slovenia.

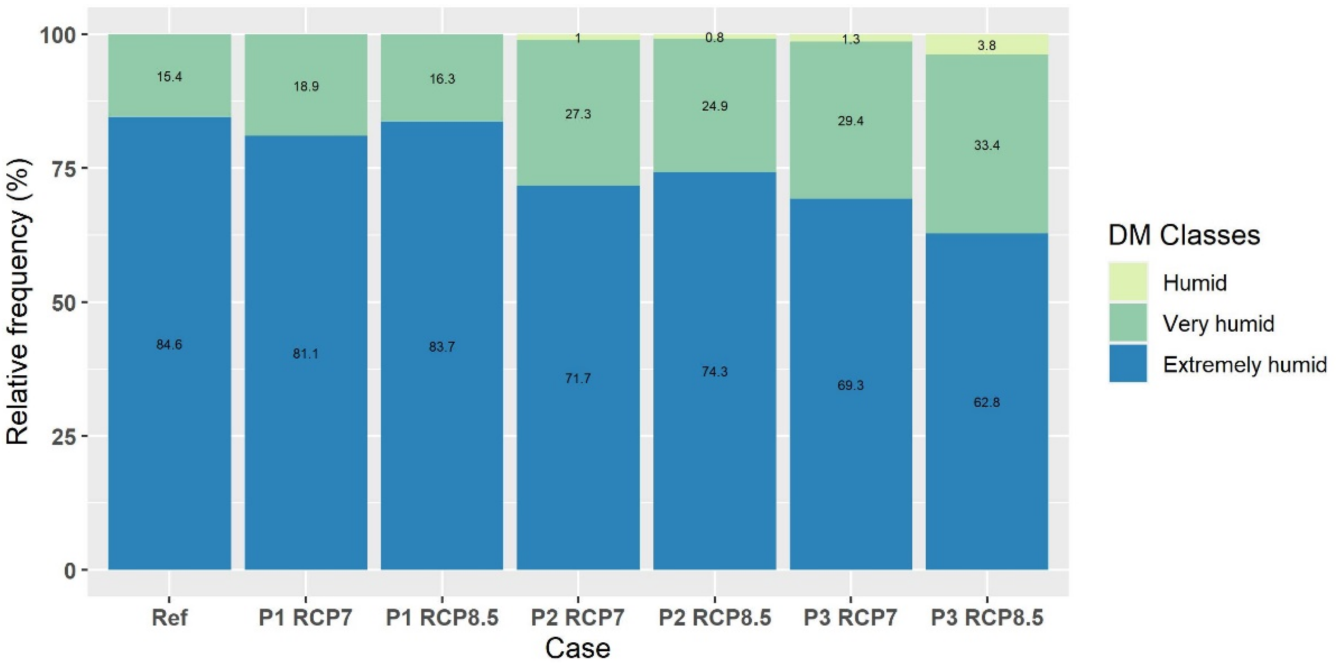

Figure 21. The relative frequency of the De Martonne classes over the natural areas of Slovenia.

3.2.1. Albania (AL)

The relative frequency of the bioclimatic classes for the agricultural areas of AL is displayed in Figure 10. It becomes evident that in relation to the Ref, a decreasing trend in the areas falling within the very humid and extremely humid bioclimate categories and the concomitant spatial increase in the areas with humid, semi-humid, and Mediterranean climates is foreseen under both investigated scenarios (RCP7 and RCP8.5). Overall, the trend for xerothermic conditions is more evident for p3 RCP8.5 given the exhibited largest decreases in the very humid (44.2% in p3 RCP8.5 vs. 51.6% in Ref) and extremely humid areas (10.5% in p3 RCP8.5 vs. 33.1% in Ref). In this case, the more intense xerothermic trend is further evidenced by the higher distribution of the Mediterranean class (6.9% in p3

RCP8.5 vs. 3.3% p3 RCP7) and in the spatially limited existence of the semi-dry class (0.5% in p3 RCP8.5). The above findings indicate that there will be higher stress for the rainfed cultivations and higher demand for the irrigated.

In comparison with the Ref, the spatial decrease in the extremely humid natural areas is illustrated for p2 and p3 of both scenarios (Figure 11), and is accompanied by increases in the very humid, humid, semi-humid, and Mediterranean areas. The largestest frequency reduction in the extremely humid class is predicted to occur in p3 RCP8.5, where approximately half of the extremely humid areas in Ref are expected to face more xerothermic conditions (37.6% in p3 RCP8.5 vs. 68.8% in Ref).

The change towards warmer and drier conditions in p3 RCP8.5, compared with the respective period of the RCP 7 scenario, is denoted by a higher frequency of the semi-humid class (2.7% in p3 RCP8.5 vs. 1.8% in p3 RCP7) and the appearance of areas with Mediterranean climate characteristics (0.4%). From the results of the maps, but mainly from the above figure, it appears that under both future scenarios, the water needs for agricultural production will increase significantly in Albania.

In corroboration with these research findings, Nistor et al. [47] have conducted a survey including the spatial distribution of the IDM in Southeastern Europe under the RCP4.5 scenario for 2011–2040 (respective p1); and for 2041–2070 (respective p2) with a lower spatial resolution (1 km^2). For both periods, results have revealed AL's bioclimate distribution among the extremely humid class in limited northern areas (respective natural areas according to Figure 1), the humid class in the western and eastern areas (agricultural areas), and the prevailing very humid class in the remaining area (natural area). Under the same scenario, a relatively small xerothermicity trend is shown for the 2nd period (2041–2070), where a reduction (increase) of the extremely humid natural areas (humid agricultural areas) is expected to occur (as demonstrated for p2 RCP7 and p2 RCP8.5).

3.2.2. Bosnia and Herzegovina (BA)

A relatively constant distribution of the very humid class results by comparison of the respective periods of both scenarios over the agricultural areas of BA (Figure 12). However, slightly higher spatial reductions of the extremely humid areas are expected to occur under the RCP7 scenario for p1 (39% vs. 45% in RCP8.5) and for p2 (23.3% vs. 26.2% in RCP8.5), and under the RCP8.5 for p3 (14.4% vs. 18.7% in RCP7), with corresponding increases in humid conditions. The more intense trend for xerothermic conditions is demonstrated for p3 RCP8.5, with additional agricultural areas being characterised by the humid (28.7% in RCP8.5 vs. 24.9% in RCP7 and 1.2% in Ref) and new areas being impacted by the more xerothermic semi-humid conditions (6.4% in RCP8.5 vs. 0.2% in RCP7 and 0% in Ref).

An overall dominance of the very humid and extremely humid classes is projected for the natural areas of BA (Figure 13), with the latter class prevailing in p1 and p2 for both scenarios. Slightly fewer natural areas are projected as extremely humid for p1 under RCP7 (65.7% vs. 70.7% in RCP8.5), for p2 (49.8% vs. 53.2% in RCP8.5), and for p3 under RCP8.5 (37% vs. 43.9% in RCP7), with corresponding fluctuations of the humid category. Concerning the Ref, the highest reduction of the extremely humid category is shown for p3 RCP8.5 (37% vs. 68.3% in Ref), where more areas will be characterised as humid (13% vs. 8.8% in RCP8.5 and 0.3% in Ref) and new areas are foreseen to undergo the effect of semi-humid conditions (1.4% vs. 0.1% in RCP8.5 and 0% in Ref).

The spatial distribution of the IDM and its spatial statistics in the region of Bosnia and Herzegovina reveal that the need for larger amounts of irrigation will gradually increase. Part of the agricultural areas of Bosnia and Herzegovina, due to the bioclimate change, will need more irrigable water (since these areas change their class from "occasional irrigations" to "supplementary irrigation"- Table 1).

For a comparison of this study's findings, the study of Nistor [47] (see 3.2.1), for both periods 2011–2040 (respective p1) and 2041-2070 (respective p2) of the RCP4.5, showed the country's bioclimate distribution among the extremely humid class in the western areas (agricultural areas according to Figure 1); the humid class in limited northeaster areas (agricultural areas according to Figure 1); and the prevailing very humid class (mostly over natural areas according to Figure 1). The expansion, however, of the agricultural areas with drier humid bioclimate is demonstrated for the 2nd period (as in p2 RCP7 and p2 RCP8.5).

3.2.3. Croatia (HR)

Results for HR reveal the consecutive spatial decrease in the very humid and extremely humid agricultural areas evidenced for all the examined periods under the RCP7, and for the p2 and p3 under the RCP8.5 (Figure 14). The latter scenario appears as more impactful on both classes' relative frequency, especially in p3, given the demonstrated higher reductions in the very humid (30.7% vs. 40.2% in p3 RCP7 and 66.2% in Ref) and the extremely humid (6.5% vs. 8.2% in p3 RCP7 and 17% in Ref) categories. The according fluctuations of the drier semi-humid class's relative frequency exhibit the highest value in p3 RCP8.5 (23.4% vs. 13.6% in P3 RCP7), where the more xerothermic environment is further evidenced by relatively limited agricultural areas projected to fall within the Mediterranean bioclimate (2.7%).

Therefore, the rural areas of Croatia from the second to the third period for both emissions scenarios will exhibit significantly increased crop irrigation demands. Relatively limited natural areas of HR are projected to face the effects of warmer and drier conditions under both scenarios in p2 and p3 (Figure 15). Similar influences on the bioclimatic regime between the two scenarios are illustrated for p2, owing to approximately the same distributions of all the resulting bioclimatic categories (semi-humid, humid, very humid, extremely humid). Nevertheless, a slight differentiation is foreseen for p3, and mostly under the RCP8.5, where higher reductions in the very humid (40.3% vs. 47.1% in p3 RCP7 and 49.2% in Ref) and the highly humid (26% vs. 28.7% in p3 RCP7 and 44.9% in Ref) areas are expected to occur. Projections for p3 RCP8.5 indicate more increased relative frequencies of the humid (24.6% vs. 19.8% in RCP7 and 5.9% in Ref) and of the drier semi-humid (8% vs. 4.4% in RCP7) and Mediterranean (1.1% vs. 0.1% in RCP7) classes, which denote a slightly higher xerothermicity of the HR's natural areas. According to Nistor [47] (see 3.2.1), HR under the RCP4.5 is characterised by the extremely humid class in the western areas (natural areas according to Figure 1), by the very humid class (both natural and agricultural areas according to Figure 1), and by the humid class in the eastern areas (agricultural areas according to Figure 1), in both examined periods 2011–2040 (respective p1) and 2041-2070 (respective p2).

Nevertheless, projections for the latter period demonstrate the expansion of the humid eastern areas (respective agricultural areas) and the appearance of the drier semi-humid over those areas (as is exhibited for p2 RCP7 and p2 RCP8.5).

3.2.4. Italy (IT)

A pronounced trend towards more xerothermic conditions is depicted for the agricultural areas of IT under both scenarios (Figure 16). Increases in the drier classes' (semi-dry, Mediterranean, semi-humid) relative frequency at the expense of the more humid classes (humid, very humid, extremely humid) are projected to occur in all time periods. The RCP7 appears more influential given an expected slightly higher limitation of the very humid and extremely humid areas in p1 and p2. More significant impacts result for p3 RCP7 and p3 RCP8.5, with the latter exhibiting the highest relative frequencies of the semi-dry (25.4% vs. 20.1% in RCP7 and 7% in Ref) and Mediterranean classes (16.6% vs. 15.7% in RCP7 and 10.2% in Ref). It is highlighted that well over half of the agricultural areas (61% in total) are expected to fall, in total, within the semi-dry, Mediterranean, and semi-humid categories, by 2100 under the RCP8.5. The above findings indicate that there is a high need for adaptation plans focused on increased evapotranspiration due to the implications of the bioclimate change. This means that the related institutions must propose strategic plans for appliable techniques for the farmers focused on soil sustainability and fertility and agricultural water management.

A tendency of the bioclimate's change towards warmer and drier conditions is displayed for the natural areas of IT under both emissions scenarios (Figure 17). The gradual increases of the drier classes' (semi-dry, Mediterranean, semi-humid) relative frequency with corresponding decreases of the more humid classes (humid, extremely humid) are projected to occur in all time periods. A slightly more intense impact is presented for the RCP7 in p1 and p2, owing to the faintly higher spatial distribution of the Mediterranean and semi-humid classes. Higher xerothermic trends, however, result for p3 RCP7 and p3 RCP8.5, with the latter exhibiting the highest relative frequencies of the semi-dry (10.3% vs. 7.5% in RCP7 and 1.7% in Ref) Mediterranean (7.7% vs. 7.3% in RCP7 and 4.1% in Ref) and semi-humid classes (9.4% vs. 8.8% in RCP7 and 5.6% in Ref).

By employing a spatial resolution of approximately 8 km, Eccel et al. [29] demonstrated no shift of the Trentino's (Northern IT, central eastern Italian Alps) very humid (vs. extremely humid in the present study as illustrated in Figure 3) bioclimate towards warmer and drier conditions by 2070 (time windows investigated were 1976–2005, 2021–2050 and 2041–2070 under the RCP4.5 and RCP8.5 emissions scenarios). Based on climate data from the 1961–1990 period, Nistor [24] investigated the spatial distribution of the IDM in the Emilia-Romagna region (Northern Italy, where the Po Plain meets the northern Apennines). The higher index values resulted in the western part corresponding to extremely humid climatic conditions. In comparison, the lower values were obtained for the eastern part, denoting semi-humid conditions, as shown in Figure 3. The researchers commented on the gradual decrease of the index's value from the southwest to the northeast of the Emilia Romagna, corresponding to a similar scheme depicted in Figure 3. Passarella et al. [32], who exploited long time series of thermo-pluviometric data (provided by 80 weather stations) from 1931 to 2010, demonstrated that approximately 40% of the agricultural Apulia region (southeastern Italy) was characterised in the past by a Mediterranean climate, nearly 30% by a semi-humid climate, and about 10% and 20% of the region fell within the semi-dry and humid categories, respectively. In the present study, the same De Martonne categories characterise the specific areas in the reference period (1981–2010), as shown in Figure 3. Furthermore, the Salento and the Ionian coastal zones were commented on as areas susceptible to increasing xerothermicity, which may trigger agricultural irrigation demands. Aramini et al. [61] have characterised the bioclimatic conditions prevailing in the Province of Cosenza (northern Calabria in the southern part of the Italian Peninsula) based on long-term (1921 to 2001) temperature and precipitation data. Results have demonstrated the distribution of the examined sites among five of De Martonne's classes in the descending order of the very humid > Mediterranean > humid > semi dry and semi humid characterisations. The same classes appear to represent Cosenza in the present study's reference period, as illustrated in Figure 3. Caloiero et al. [34], who performed a bioclimatic analysis over the entire Calabrian region for the 1916–2010 time period, demonstrated the subdivision of the area into four bioclimatic zones. These zones were characterised by the hyper-humid (IDM over 60), humid (IDM: 30–60), sub-humid (IDM: 20–30), and semi-dry (IDM: 15–20) categories, with approximately 3% of the area (the Ionian coastal side) lying within the latter category, and 60% of the area being classified as humid. The authors denoted the forest cover change over the area, possibly owing to the marked increase of the sub-humid class. Similarities are depicted for the same region in Figure 3, with the more xerothermic classes (semi-humid, Mediterranean) characterising the Ionian coastal areas, and the more humid classes (humid, extremely humid) occupying a significant part of the Calabrian region. These findings are also supported by Pellicone et al. [40], who demonstrated the dominating humid character of Calabria's bioclimate, with only the region's coastal areas characterised by more xerothermic conditions over the period 1951–2016.

3.2.5. Montenegro (ME)

In most cases, the bioclimatic regime of ME's agricultural areas is distributed among the very humid and extremely humid classes (Figure 18). These conditions dominate, exhibiting a practically unchanged total spatiotemporal relative frequency. The slight effect of the more xerothermic conditions is apparent in p2 and p3 for both scenarios with slightly more extended very humid areas resulting for the latter period under RCP8.5 (30.9% vs. 27.7% in RCP7 and 10.7% in Ref), accompanied by a faintly increased expansion of the humid areas (0.6% vs. 0.1% in RCP7).

Despite the bioclimatic shift that also is expected to take place in this mountainous Adriatic country, the scenarios examined do not seem to suggest a decisive increase in the irrigation requirements of crops. Overall, most of the natural areas of ME are impacted by extremely humid bioclimatic conditions in Ref, p1 RCP7 and p1 RCP8.5 (Figure 19), between which the relative frequency remains approximately constant (95.6 %, 95.3 %, and 96.8 %, in Ref, p1 RCP7, and p1 RCP8.5, respectively). A slight tendency towards warmer and drier bioclimatic conditions is evident for p2, where the identical less-extended distribution of the extremely humid class is demonstrated for both scenarios (90% for p2 RCP7 and p2 RCP8.5). This continuous trend is also illustrated for p3 for both scenarios, with the RCP8.5 being more impactful given the projected appearance of the drier humid class over very limited natural areas (0.2%).

Based on calculations of the IDM, Nistor [47] (see Section 3.2.1) reveals the domination by extremely humid conditions of the ME's natural areas in 2011–2040 (respective p1) under the RCP4.5. More xerothermic conditions appear in 2041–2070 (respective p2) in which the expansion of the less humid natural areas falling within the very humid class occurs (as in the p2 period of both scenarios, RCP7, and RCP8.5). According to the bioclimatic classification conducted by Brđanin and Sedlak [46] for a relatively short time frame 2009–2018, the Lim valley (eastern Montenegro) has been characterised by extremely humid and very humid conditions (as in the Ref for both natural and agricultural areas).

3.2.6. Slovenia (SI)

According to the resulting projections, the very humid and extremely humid bioclimatic conditions are expected to dominate the agricultural areas of SI under both examined emissions scenarios (Figure 20). However, a decrease is demonstrated for the extremely humid category, mostly evidenced under the RCP8.5, and particularly in p3 (35.9% vs. 42.8% in RCP7 and 63.1% in Ref) where additional areas are predicted to fall within the more xerothermic humid category (11.6% vs. 5% in RCP7).

A tendency towards warmer and drier conditions is projected for the natural areas of SI (Figure 21), owing to the temporal increase of the humid and very humid classes' spatial distribution at the expense of the dominating extremely humid category. This trend is projected for both scenarios, with an overall higher impact resulting from the extreme RCP8.5. Furthermore, these alterations are mostly evident for p3 RCP8.5, where a larger reduction of the extremely humid class (62.8% vs. 69.3% in p3 RCP7 and 84.6% in Ref) and concomitant increases of the very humid (33.4% vs. 29.4% in p3 RCP7 and 15.4% in Ref) and humid (3.8% vs. 1.3% in p3 RCP7) classes are foreseen to take place.

According to the results by Nistor [47] (see Section 3.2.1) for the 2011–2040 period (respective p1) under the RCP4.5, SI consists of the prevailing extremely humid areas (natural areas according to Figure 1) and the remaining very humid areas (agricultural areas along the eastern borderline). For the period 2041–2070 (respective p2), projections reveal a limited expansion of the very humid agricultural areas in place of the respective extremely humid ones, as in the p2 of the RCP7 and RCP8.5 scenarios.

4. Conclusions

In general, the findings of this study reveal a constant tendency for more intense xerothermic (hot and dry) conditions at every studied time period and for every emissions scenario. This environmental alteration will cause increased evapotranspiration, which will drive higher demand for water supply via irrigation in the irrigated crops. In the case of rainfed crops, forests and other natural areas will face more stressful conditions. Thus, the presented and analysed bioclimatic changes of the Adriatic Sea countries must be considered for the natural areas management and agricultural sectors transformation, to maintain their sustainability.

On a territorial level, the recorded change in the bioclimate conditions is undeniable (see Figures S1 and S2 in the Supplementary Material document). Independently of the examined emissions scenario, the bioclimate zones over the entire ADT are distributed within 6 of the 7 De Martonne categories (semi-dry, mediterranean, semi-humid, humid, very humid, and extremely humid). In the agricultural areas of the ADT, the humid class surface remains almost stable between the examined scenarios. The more humid classes (very humid and extremely humid) are shrinking, and the more xerothermic classes (semi-humid, mediterranean, and semi-dry) expanding, according to the projections (Figure S1). For the natural areas, the boarded bioclimatic class is the very humid (which remains almost stable in terms of the relative surface of the ADT). Thus, the more xerothermic classes (humid, semi-humid, mediterranean, and semi–dry) are increasing, and the more humid (extremely humid) are decreasing (Figure S2).

The western ADT exhibits a more intense aridisation scheme in contrast to the eastern regions, where a more humid regime is projected to still be present by 2100. Areas foreseen to be subjected to more xerothermic conditions include Italy's natural and agricultural landscapes (Italian Peninsula, Sicily, Sardinia), with the latter being more influenced by bioclimate change. More intensified warming and drying are demonstrated for the 2071–2100 timeframe under the extreme RCP8.5 emissions scenario. Projections for most individual country regions indicate an evolution of the natural and agricultural areas' bioclimate, that lies in the gradual spatiotemporal dominance of a more xerothermic regime appearing as more intense under the extreme RCP8.5 scenario for the agricultural areas. The semi-dry, Mediterranean, and semi-humid De Martonne bioclimatic categories exhibit substantial spatial distribution over Italy, with the former category dominating the southern and western parts of the country, especially under the RCP8.5 by 2100. The transition towards more xerothermic conditions will trigger the necessity for the fulfillment of higher irrigation demands in agriculture.

Overall, the foreseen ADT's bioclimate alterations highlight the substantial aridisation in the future attributed to the prevalence of the long-term (2071–2100) evolution of the more intense xerothermic conditions under the extreme RCP8.5 emissions scenario. Finally, the feasibility and functionality of the De Martonne index for illustrating the Adriatic region's bioclimatic footprint, and its upcoming future alteration over the territory's natural and agricultural areas, is demonstrated. The institutions and government services could fine-tune their adaptation plans for the agricultural and natural areas using the provided De Martonne's index spatial distribution for future periods, greenhouse gas emissions scenarios, and country-level spatial statistics.

The future bioclimatic conditions indicate more xerothermic conditions under every examined greenhouse gas emissions scenario. Thus, the related institutions and services must conceive end implement plans for the conservation of natural areas and agricultural sector sustainability. Moreover, climate services must be utilised in order to circulate crucial climate information bottom-up, and vice versa. The aim of the aforementioned plans and services is the most effective management of natural resources, such as soil and water, for a more productive agricultural sector and healthy natural ecosystems. In addition, it is of utmost importance that the worldwide community must intensify the effort to reduce greenhouse gass emissions and to implement, as soon as possible, mitigation and adaptation plans, especially in areas like the one studied.

Future research will involve the extension of our investigation on the impacts of climate change on the bioclimatic regime of agricultural, natural, and urban areas of southeastern Europe by employing alternative bioclimatic indices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15064867/s1, Figure S1: The relative frequency of the De Martonne classes over the agricultural areas of the entire study area; Figure S2: The relative frequency of the De Martonne classes over the natural areas of the entire study area.

Author Contributions: Conceptualization, I.C.; Methodology, I.C.; Investigation, F.D. and I.C.; Resources, F.D.; Original Preparation and Writing, F.D.; Writing on Data and Method, I.C. and J.E.; Method Application and computation of Results, I.C.; Table and Figures, I.C.; Review and Editing, F.D., I.C and J.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: High resolution maps which are presented in this study are available upon request.

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

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