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A High-Resolution Analysis of the de Martonne and Emberger Indices Under Different Climate Change Scenarios: Implications on the Natural and Agricultural Landscape of Northeastern Greece

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Abstract: This article explores the impacts of climate change on the rural and natural landscapes at the Region of Eastern Macedonia and Thrace, Northeastern Greece. The spatial distributions of the bioclimatic de Martonne and phytoclimatic Emberger indices were calculated, at very high resolution (~500m), for the present conditions (1970–2000), two future time periods (2030–2060; 2070–2100) and for two greenhouse gas emission scenarios (RCP4.5; RCP8.5). The results show significant bioclimatic changes, especially in the Rhodope Mountain range and almost along the whole length of the Greek-Bulgarian border, where forests of high ecosystem value are located, together with the rural areas along the Evros river valley, as well as in the coastal zone of the Aegean Sea. The article describes the processes of bioclimatic changes that can significantly modify the landscapes of the study area. The study's results reveal spatiotemporal shift towards more xerothermic environments under both scenarios. Independently of the employed indices, profound bioclimatic alterations are projected for the long-term timeframe of the extreme RCP8.5 scenario. According to the de Martonne outcomes, the more xerothermic Mediterranean and Semi-humid conditions are projected to impact the eastern, southern, and western agricultural landscapes (approximately 40% of the investigated area), the sustainability of which will depend on supplementary irrigation. Implementation of the Emberger index points out that by the year 2100, the natural and agricultural landscapes (distribution of ~ 42%) will be subjected to the Sub-humid, Mild winter, the Sub-humid, Cool winter (~33%) and the even more dry-thermal Humid/Sub-humid, Warm winter conditions (~5%). Based on these foreseen futures, initial interpretations for key landscape conservation, natural capital and ecosystem services management are proposed.

Keywords: climate change; bioclimate; agricultural areas; natural areas; natural capital; ecosystem services; protected area management; Southeastern Europe; support decision making

1. Introduction

Climate is the main driver of natural vegetation and agricultural landscape evolution [1,2]. Understanding the effects of climate, both currently and in the near and far future, is one of the most critical aspects of effective planning for landscape conservation, management and agricultural sustainability. The warm-temperate regions of the world, distinctive biomes characterized by dry summers and wet winters (Mediterranean climate), are especially vulnerable to the effects of climatic variability and the change of climate [3]. This is critically important in the Mediterranean, where a long-term co-evolution of natural and cultural landscape is documented [4]. Mediterranean Europe provides examples of some of the most complex and heterogenous landscapes and local climatic conditions in the Continent, rendering intriguing problems in climate-driven landscape change prediction [5] and climate-change adaptation planning. In fact, in recent times, effort has been invested into re-evaluating the historical impact on traditional landscape development; it has long been said that the euro-Mediterranean is too complex to allow for simple generalizations [6].

The anthropogenic induced climate change (CC) ranks high in the hierarchy of scientific interests owing to its expeditious spatiotemporal development and menacing nature [7]. The associated modified bioclimate poses considerable threats to the survival of living organisms, the sustainability of natural landscapes, the viability of agricultural activity, the conservation of natural resources, the maintenance, improvement, deterioration or loss of ecosystem services, and the efficiency of management policies [8–14].

In the coming decades, Greece will appear as climatically pressurized owing to the marked transformation of the bioclimate that is already arising over the entire territory [15–17]. CC projections demonstrate notable warming under the impact of the extreme RCP8.5 climatic scenario [18,19]. By the year 2100, the near-surface temperature is expected to rise by an average value of 4.3 ◦C, resulting, thus, in a significant increase of the night frosts, continual dry spell days, the annual number of hot days and tropical nights, the growing season length and a reduction of frost days. The foreseen increase in the annual number of consecutive dry days by 30% (15.4 days) and the concomitant decline by 16% to 40% of the seasonal precipitation, underline a crucially drier bioclimatic footprint in the years to come [20–23]. Additionally, in the overall concept of both the projected and observed CC, the present and expected extreme weather events appear as more frequent and intensified (e.g., more severe and prolonged drought events; earlier start and later ending of heatwaves period; increasing trends of heavy precipitation), highlighting the climate crisis impacts on human security [24–27].

Climate projections over Greece in conjunction with its present rather dry-thermal climatic regime give grounds for the country's escalating susceptibility to the phenomenon of CC which may induce far-reaching impacts on its extensive natural ecosystems and highly heterogeneous agricultural sector [28,29].

Several present and foreseen effects of CC on the natural landscapes of Greece include significant habitat alterations and elevated extinction risk for autochthonous species and vegetation communities (see e.g., *Juniperus drupacea* forests of Greece) [30], increase in drought-related tree dieback [31], declining tree productivity and development [32], reduction in habitat-suitable areas [33], projected altitudinal and elevational shifts and extinctions of endemic species [34,35], spatial redistribution of species, invasions and biodiversity loss [36], increased likelihood of severe wildfires and floods [37,38] and projected altered fire behavior [39].

Some of the CC impacts related to rural and agricultural areas may involve the northward shift of the agro-climatic zones [40], crop production quality decline and quantity limitation [17,41], effects on the capacity of crops to adapt [42], increased susceptibility of crops to extreme weather [43], differentiations in the geographical expansion of cultivations [44], alterations in the cultivation area suitability [45], soil erosion and risk for land desertification [46], impacts on groundwater quantity and quality, limitation of surface water availability [47,48], changes in crop phenology [49], increased growing season length [50] and negative social and economic development trends in rural areas [51].

Temperature and precipitation are fundamental climatic parameters and are decisive inputs for the investigation of CC. However, the overall apprehension and magnitude of CC and the comprehension of its impacts on vegetation and vegetation types' distribution is far more expressed and achieved by applying bioclimatic indices [52–54]. The bioclimatic indices' major significance as tools for categorizing bioclimates is indisputably exhibited by their broad exploitation in climatological, bioclimatological, and agricultural research studies [55–57].

Approximately one hundred years ago, the de Martonne bioclimatic index (DMI) was proposed for the evaluation of a specific environment's dryness degree by categorizing it into seven (7) classes, from "dry" to "extremely humid" based on the fundamental climatic parameters of air temperature and precipitation [58,59]. The DMI has been extensively implemented for the classification of the bioclimate due to its reliability, effectiveness, and validity [60,61]. Scientific investigations, that frequently employ the DMI, fall within the fields of climatology/bioclimatology and agricultural and land or water resources management, while the index also appears as a serviceable tool for achieving environmental assessment reports [60,62–65].

The Emberger index (EI), commonly described as the "pluviothermic quotient Q", categorizes the Mediterranean area's bioclimate zones corresponding to a scheme extending from the "Per-Humid" to the "Per-Arid" type of bioclimate or bioclimatic category established on the parameters of temperature, precipitation, and evaporation. Estimations of the EI include the representation of the annual temperature by the average maximum temperature value of the hottest month (M) and the average minimum value of the coldest month (m), considering that the growth of vegetation appears dependable on these thermal limits. Precipitation (P) is expressed on an annual basis. At the same time, evaporation is indirectly represented by the difference between the two temperature values (M—m), owing to the EI's increase with the latter parameter [66–68]. Also, a simplified algorithm based on the minimum winter temperature (m) falling within the range of the "Very Hot" to the "Very Cold" temperature characterizations is applied, serving the purpose of the phytoclimate classification in bioclimatic subtypes, often termed as the 'Q2' [68,69]. Thus, an area's phytoclimatic footprint is characterized through the combination of the bioclimatic types of characterizations derived from the estimates of the Q values along with the temperature conditions based on the estimates of the m values, which results in the Emberger's Q2 bioclimatic subtypes; for example, a Q2 subtype may be described as the "Semi-arid, Mild winter" subtype.

Within the changing climate's research framework, studies involving the implementation of the DMI and EI indexes are rather limited in Greece. For example, Baltas [70] has denoted the variability of aridity in Northern Greece from 1965 to 1995 as derived from the DMI characterization range of the Semidry to the Very humid bioclimate. The same author estimated the bioclimatic footprint of the entire country which was described by the Dry to the Very humid classes. Another study in Northern Greece conducted by Mattas et al. [71] on the upper agricultural area of the Gallikos river basin has revealed bioclimatic variations from the Semiarid to the Humid conditions based on climatic data of a 27-year period (1980–2006). Also, mountainous regions have been classified by Sidiropoulou et al. [72], who have characterized respectively Northern Greece's Mt Vermio and Southern Greece's Mt Zireia as moderately humid and humid, respectively on the basis of climatic data during the years 1990–2019. Lappas et al. [73] have revealed the bioclimatic conditions of a water district in eastern–central Greece illustrated by the Arid to Very humid classes over the 1980 to 2001 timeframe. A moderate trend, between the years 1958 and 2011, towards a more dry-thermal regime over the traditional agroforest system of Thriasio Plain (Northwest Athens) has been exhibited by Mavrakis et al. [74]. Further south, Beloiu et al. [75] pinpoints the transition of Crete Island's bioclimate from Very humid to Humid conditions over the 1979–2013 period.

According to the recent findings of Charalampopoulos et al., 2023 [19] for the Greek territory, by 2100 and under the RCP8.5, the semidry bioclimatic conditions are expected to prevail over a significant percentage natural landscape area of approximately 34%, followed by the Mediterranean regime (percentage area of nearly 19%) and the most xerothermic dry bioclimate (very limited area of 0.1%). Also, profound trends towards the more dry-thermal regime are exhibited for the agricultural areas where the semidry conditions are projected to influence substantial parts under both the RCP7 (area of 53.9%) and RCP8.5 (area of 60%), by the end of the century. The authors point out that the sustainability of the 'Semidry' agricultural areas will depend entirely on water supply through appropriate irrigation schemes, while the areas with Mediterranean bioclimatic characteristics (nearly 20% for both scenarios) are expected to satisfy their water needs through supplementary irrigation. These evolutionary situations raise uncertainty for the future of the agricultural sector by considering severe impacts on Greece's production capacity.

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Evidently, most utilizations of the DMI concern bioclimatic studies based on past timeframes, while there has been no application of the EI until recently and over the entire country involving past, present, but also future time-periods [18,19]. This highlights the limited scientific knowledge on the future bioclimatic development on a local scale over the natural and agricultural areas, with no applications of the DMI and EI as tools for bioclimatic categorization and for projections on conditions foreseen on a local scale in Greece, owing to CC.

Motivation, therefore, for the conduction of the present investigation lies in the relatively limited scientific outcomes related to the DMI and EI applications, along with the critical need for the protection and preservation of the natural and agricultural landscapes already threatened by the changing bioclimatic conditions.

More specifically, in this study, both the bioclimatic DMI and phytoclimatic EI indices are computed. Their categories are spatiotemporally illustrated, for the first time, for the present (1970–2000) and future (2030–2060; 2070–2100) climate conditions at very high resolution (~500m) and under two specific greenhouse gas emission scenarios, namely the RCP4.5 and RCP8.5.

Overall, and under the framework of the LIFE-IP AdaptInGR National Project, the main objective of the present study is to outline the major short-term and long-term bioclimatic alteration trends that are foreseen to occur and shall undoubtedly impact the already pressurized natural and anthropogenic ecosystems in Northern Greece. The resulting mapping of the spatial distributions of the indices' classes, coupled with the spatial statistics per class, period, and emission scenario, may serve as useful tools for conducting further environmental research in the broader framework on the conservation of landscapes threatened by CC. The final outcomes aim to support decision and policy making for regional natural capital, ecosystem services, and agricultural development management to adapt in, and mitigate future predicted conditions.

2. Materials and Methods

2.1. Study Area

The study area (Figure **Error! Reference source not found.**) is the administrative region of Eastern Macedonia and Thrace (EMTh) (NUTS code EL51), located in northeastern Greece. The region's area is 14,157.76 km^{2,} with a population of 562,201 residents. It is characterized by a diverse landscape variety consisting of mountainous areas in the northern part and an extensive coastline in the southern part. Climatically, the area lies between two warm temperate climate zones, influenced by the more continental Eastern European and Mediterranean [76].

In the study area, there are four National Parks (National Park of Rodhopi mountain range, National Park of Nestos Delta and Vistonida and Ismarida lagoons, National Park of Dadia and National Park of Evros Delta) and 41 Natura 2000 sites that are either fully or partially located within the region's boundaries. These protected areas serve as essential ecological corridors and are part of Greece's commitment to the Natura 2000 network, the largest coordinated network of protected areas globally. These sites include both Special Areas of Conservation (SACs) and Special Protection Areas (SPAs), designated under EU Directives to conserve habitats, species, and avian populations of particular ecological significance. Characteristic examples of key Natura 2000 Sites in the Region are (a) the Delta Evrou (SPA), a vital wetland area supporting migratory bird species, (b) the Delta Nestou kai Limnothalasses Keramotis - Evryteri Periochi kai Paraktia Zoni (SAC), known for its rich biodiversity in riparian, wetland and coastal habitats, (c) the Vouna Evrou - Potamos Lyras - Spilaia Didymoteichou kai Kefalovounou, important for raptors and diverse flora and fauna, (d) the Limnes Vistonis, Ismaris - Limnothalasses Porto Lagos, Alyki Ptelea, Xirolimni, Karatza, a wetland system supporting various species and habitats and (e) the Kentriki Rodopi kai Koilada Nestou, that includes unique forest ecosystems and rare flora and fauna species (see https://natura2000.eea.europa.eu/).

Natural and agricultural formations are fairly well balanced within the region, and this creates a condition of heterogenous landscape patterns, including areas of traditional farming and livestock grazing among both intensive agricultural lowlands and less-developed uplands. Upland areas include varied landscape forms dominated by semi-natural and natural woodland vegetation [77]; in contrast with the intensive farmland areas, where the vegetation may be considered as 'natural' in terms of its constituent floral composition [78]. At the regional scale, these natural areas cover 55.8%, while agricultural areas cover 37.8% (in green and yellow, respectively, Figure **Error! Reference source not found.**). The Corine Land Cover has made the generalized demarcation of the natural and agricultural areas [79] dataset, in which several subclasses of the natural and agricultural landcover merged into two main classes. Artificial land-cover, predominantly the main conurbations, including towns and villages, are mostly located in the agricultural areas.

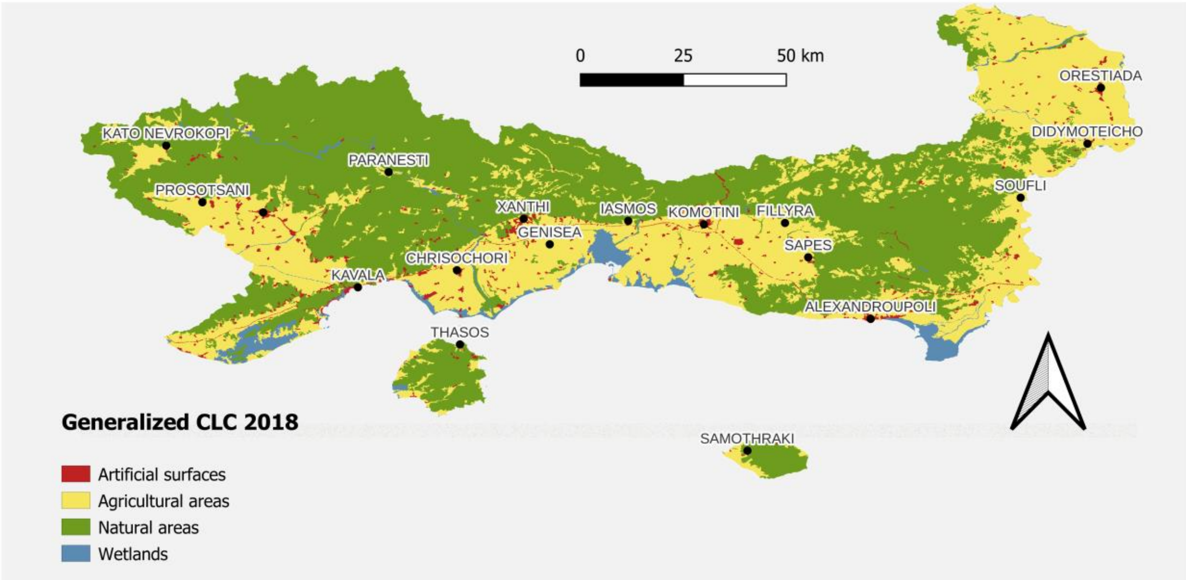

Figure 1. Generalized land cover (Corine Land Cover 2018).

It is exhibited that the agricultural areas cover the southern part of the study area, near the shoreline, while the natural areas are scattered in the northern part, on the mountainous regions and in major parts of the Samothraki and Thasos islands. Moreover, it is illustrated that the northeastern and eastern parts of the study area have been classified as agricultural areas.

2.2. Data and Methods

Daily simulations of several meteorological variables from eight ensemble members of the Regional Climate Models (or GCM - RCM pairs) from the EU-RO-CORDEX data base (https://www.euro-cordex.net), - available at the Climate Data Store (https://cds.climate.copernicus.eu) of the European "Copernicus Climate Change Service" with a horizontal resolution of 0.11^{o} were used for the Region of East Macedonia–Thrace (Greece).

Specifically, the eight regional climate models (Table 1) are:

The RCA4 regional climate model of the Swedish Meteorological and Hydrological Institute (SMHI) driven by two (2) different global climate models: 1: the HadGEM2-ES of the Met Office Hadley Centre (RCA4-MOHC) and 2: the MPI-ESM-LR of the Max Planck Institute for Meteorology (RCA4-MPI).

The HIRHAM5 regional climate model of the Danish Meteorological Institute (DMI) driven by the EC-EARTH global climate model (HIRHAM5-EC EARTH).

The CCLM4-8-17 regional climate model of the Danish Meteorological Institute (DMI) driven by EC-EARTH global climate model (CCLM4817-EC EARTH).

The RACMO22E regional climate model of the Royal Netherlands Meteorological Institute (KNMI) driven by 2 different global climate models: 5: the CNRM-CM5 of the Météo France Institute (RAC-MO22-CNRM) and 6: the HadGEM-ES of the Met Office Hadley Centre (RAC-MO22-MOHC).

The regional climate model REMO2009 of the Max Planck Institute driven by the MPI-M-MPI-ESM-LR global climate model (REMO2009-MPI).

The RAC-MO22E regional climate model of the Royal Netherlands Meteorological Institute (KNMI) driven by the EC-EARTH global climate model (RACMO22-EC EARTH).

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The climatic / meteorological parameters extracted for the Region of East Macedonia–Thrace are the daily temperatures (mean, maximum, minimum), precipitation, wind speed, relative humidity, evapotranspiration, snowfall and sunshine duration. The ensemble mean of these climate parameters' simulations was also used to estimate climate indices related to the natural landscape, such as the fire weather index and the dry days. The data cover the 1971–2100 period under two Representative Concentration Pathways – RCP [80,81] (Figure **Error! Reference source not found.**) emissions scenarios, namely the RCP4.5 and the RCP8.5. The analysis is performed for three time periods, 1971–2000, which is used as the reference period and two future periods, 2031–2060 and 2071–2100.

Table 1. The applied Regional Climate Models (RCMs).

Institute	RCM (Regional Climate Model)	GCM (Global Climate Model)	RCMs (GCM/RCMpair)
SMHI	RCA4	HadGEM2-ES MPI-ESM-LR	1.RCA4-MOHC 2. RCA4-MPI
DMI	HIRHAM5 CCLM4-8-17	EC-EARTH	3.HIRHAM5 4.CCLM4817
KNMI	RACMO22E	CNRM-CM5 HadGEM2-ES EC-EARTH	5.RACMO22-CNRM 6.RACMO22-MOHC 8.RACMO22-ECEARTH
MPI-CSC	REMO2009	MPI-M-MPI-ESM-LR	7.REMO2009-MPI

Daily simulations of several climate parameters for the area of interest (East Macedonia-Thrace), were extracted: mean – Tmean, maximum – Tmax and minimum – Tmin temperatures, total precipitation – PR, mean wind speed – Wind, relative humidity – RH, evapotranspiration –ET, sunshine duration – SD and snowfall-PRSN. The simulations cover three time periods: historical (1971–2000), near future (2031–2060), and distant future (2071–2100). Future simulations are conducted under two CC scenarios based on the IPCC's (https://www.ipcc.ch) Representative Concentration Pathways – RCP (IPCC 2014, van Vuuren et al., 2011, Figure 1) and specifically, the RCP4.5 (medium mitigation efforts) and the RCP8.5 (high emission scenario with no climate mitigation policies) (Figure **Error! Reference source not found.**).

The RCP4.5 is a stabilization scenario where total radiative forcing is stabilized before the year 2100 by the employment of a range of technologies and strategies for reducing greenhouse gas emissions [82]. The RCP8.5 is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the literature leading to high green-house gas concentration levels [83].

In addition, climate indices related to natural and agricultural landscapes, such as the maximum length of continuous drought days, number of dry days, and number of days with high precipitation, have been calculated based on the ensemble mean of the selected EURO-CORDEX climate models under the two emission scenarios (RCP4.5; RCP8.5). For the evapotranspiration projections/simulations, a subset of two RCMs was used (the 1 and 2 in Table **Error! Reference source not found.**).

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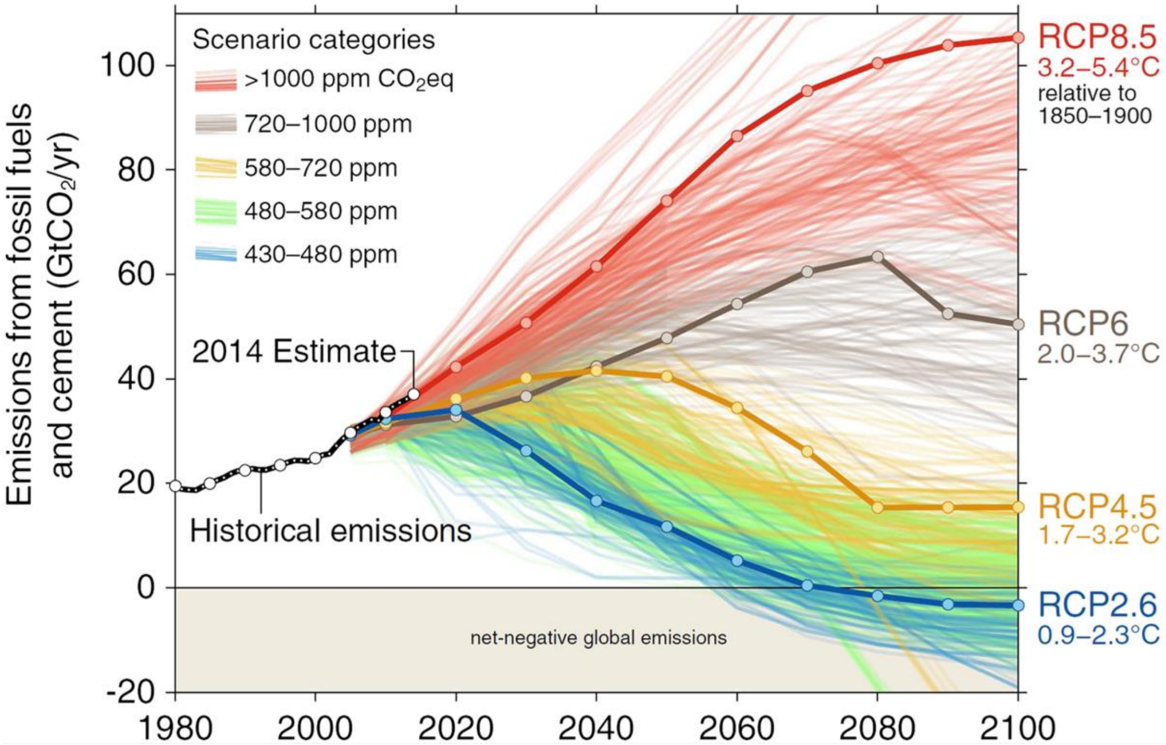

Figure 2. Representative Concentration Pathways (RCPs) used in this study: RCP4.5 (moderately ambitious mitigation policies) and RCP8.5 (business as usual, no mitigation). As depicted, the historical emissions currently follow the RCP8.5 pathway [84].

For the precipitation projections/simulations the ensemble mean of 3 RCMs (5, 6 and 8, in Table 1) is utilized, after evaluation, that represent better the area of interest in terms of rainfall. For the analysis of all climate parameters required as inputs for the calculation of the bioclimatic indices and related climate indices, the ensemble mean of the 1 to 7 RCMs is implemented. All climate data are employed as an ensemble mean of the respective sub-set of the RCMs model simulations spanning from 1971 to 2100. Projections' climate parameters and indices maps are constructed using geo-spatial models' outputs and the GIS tool. While the horizontal spatial resolution of the simulations is 0.11° (approx. 12 km), the analysis of the maps is 500m following the application of the ArcGIS spatial interpolation method of the Natural Neighbor in the initial data. Maps depict the current climate during the reference period (Ref: 1971–2000) as well as changes between the near (P1: 2031–2060) or distant future period (P2: 2071–2100) and the reference period,

2.2.2. Bioclimatic Indices' Calculations

2.2.2.1. The de Martonne Index (DMI)

For the assessment of the bioclimatic conditions of the cross-section area, the DMI was applied and computed on an annual basis according to the following formula:

$$DMI = \frac{P}{10+T}$$

where:
P: is the annual average precipitation (mm),
T: is the annual average air temperature (°C) and
10: is the coefficient employed for the acquisition of positive values.

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Table 2. The de Martonne Index (DMI) categorisation, according to Passarella et al. [85].

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

2.2.2.2. The Emberger Index (EI)

For the assessment of the phytoclimatic conditions of the cross-section area, the Emberger index (EI), commonly termed as the 'pluviothermic quotient' (Q or Q1) was applied and computed on an annual basis according to the following formula:

$$EI = Q = \frac{1000 * P}{\left[\frac{M+m}{2}\right] * (M-m)} \Rightarrow Q = \frac{2000 * P}{M^2 - m^2}$$

where:
P: represents the annual average precipitation (mm),
M: represents the average monthly air temperature of the warmest month in absolute degrees (K) and
m: represents the average monthly air temperature of the coldest month in absolute degrees (K).

Table 3. Phytoclimatic classification of the Emberger's pluviothermic quotient (Q) by Derdous et al. [86].

EI or Q values	**Types of bioclimates**
Q > 170	Hyper-humid (or Per-humid)
120 ≤ Q ≤ 170	Humid
65 ≤ Q < 120	Sub-humid
30 ≤ Q < 65	Semi-arid
10 ≤ Q < 30	Arid
Q < 10	Hyper-arid (or Per-arid)

The final characterization of the Q2 types is the combination of the Q and the m characterizations, as presented in Table 4. For example, when calculating the Q as 67 and the m as 2 °C, the resulting Q2 classification is the 'Sub-humid, Cool winter'.

Table 4. Modified classification of temperature based on the values of m.

m (°C)	**Temperature conditions**
m > 7 °C	Warm winter
3 °C < m ≤ 7 °C	Mild winter
0 °C < m ≤ 3 °C	Cool winter
-10 °C < m ≤ 0 °C	Cold winter
m ≤ -10 °C	Very cold winter

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3. Results and Discussion

Henceforth, corresponding to the examined time periods and emission scenarios, abbreviations will include the following: Ref (reference historical period 1970–2000), P1 RCP4.5 (first future period P1: 2030–2060, under the RCP4.5 scenario), P2 RCP4.5 (second future period P2: 2070–2100, under the RCP4.5), P1 RCP8.5 (P1 under the RCP8.5 scenario) and the P2 RCP8.5 (P2 under the RCP8.5).

3.1. The Spatial Distribution of the de Martonne Index (DMI)

According to the resulting illustration (Figure **Error! Reference source not found.**) the reference period's (Ref) bioclimate is distributed among five (5) DMI classes ranging from the Extremely humid to the Mediterranean (Extremely humid, Very humid, Humid, Semi-humid, and Mediterranean). The domination of the Very humid category (51.3% spatial distribution, Figure **Error! Reference source not found.**), followed in descending order mainly by the Humid (24.1%), and Semi-humid (12.6%) bioclimates, is apparent. The Extremely humid (11%) and Very humid climates are exhibited over the natural semi-mountainous and mountainous inland areas of higher altitudes, while the more xerothermic Semi-humid (12.6%) and less expanded Mediterranean (1.1%) climates correspond to the lowland agricultural plains in the south (along the coastline and adjacent to the sea) and the northeastern part of the region of the EMTh.

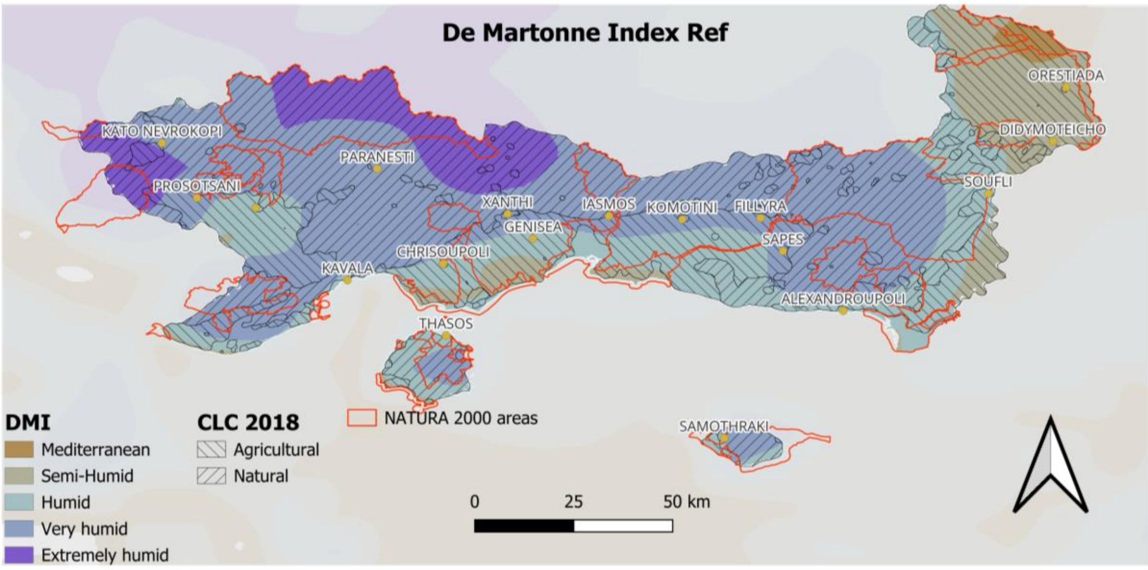

Figure 3. De Martonne Index spatial distribution for the reference period (Ref: 1970–2000).

The same five DMI classes (Extremely humid, Very humid, Humid, Sub-humid, and Mediterranean) result for the investigated P1 RCP4.5 (Figure **Error! Reference source not found.**), in relation to the respective in the Ref (Figure **Error! Reference source not found.**). However, a slight decreasing spatial trend of the Humid (from 24.1% in the Ref to 23.8% in P1 RCP4.5, Figure **Error! Reference source not found.**), Very humid (from 51.3% to 49.4%), and mostly of the Extremely humid (from 11% to 6.6%), is documented. Such future alterations appear as favorable, especially to the Semi-humid conditions, which are expected to influence additional agricultural areas (from 12.6% in the Ref to 18.8% in P1 RCP4.5, Figure **Error! Reference source not found.**) in the western, southern, and eastern parts of the EMTh. It is evident that, by 2060, more rural land will be in need of supplementary irrigation arising therefore, high concerns given the hypothetical effect of a relatively optimum scenario such as the RCP4.5.

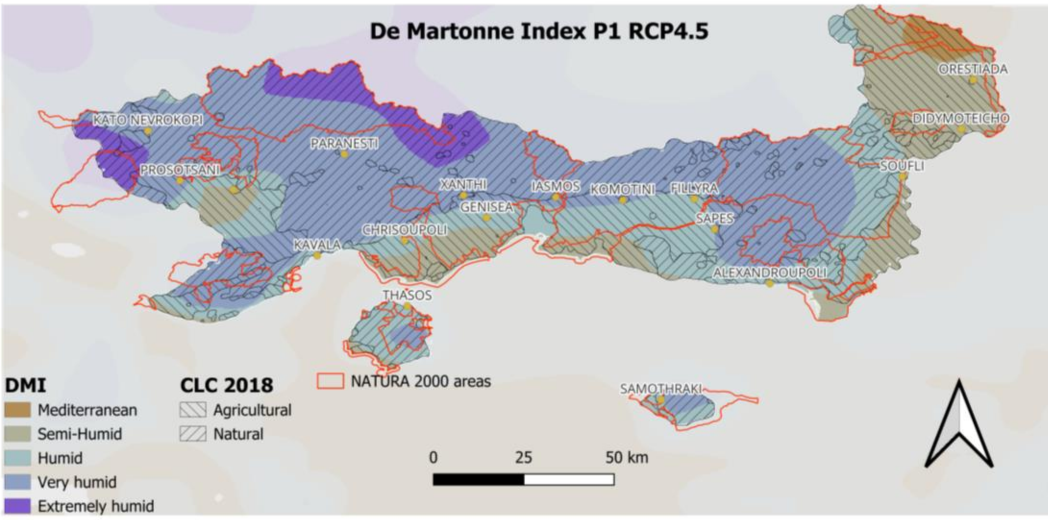

Figure 4. De Martonne Index spatial distribution for the time period 2030–2060 under the RCP4.5 scenario.

In comparison with the previous cases (Ref and P1 RCP4.5, respectively, in Figures **Error! Reference source not found.** and **Error! Reference source not found.**), minor bioclimatic evolutions are depicted also for the P2 RCP4.5 (Figure **Error! Reference source not found.**). Changes concern mostly the continuation of the xerothermic trend exhibited by the further distribution limitation of the Extremely humid class over the northern and western natural areas (from 11% in the Ref to 6.6% in P1 RCP4.5 and 4.6% in P2 RCP4.5, Figure **Error! Reference source not found.**) and the support of the Mediterranean conditions which are now more expanded over the northeastern agricultural areas (from 1.1% in the Ref to 1.5% in P1 RCP4.5 and 2.1% in P2 RCP4.5, Figure **Error! Reference source not found.**). As such, by the year 2100, the supplementary irrigation techniques shall appear as mandatory in wider critical lowland areas affected by the Mediterranean (in the northeast), which in addition to the Semi-humid bioclimate's coverage (in the west, along the coastal zone and the east) both correspond to a total spatial distribution of 21% over the EMTh (Figure **Error! Reference source not found.**).

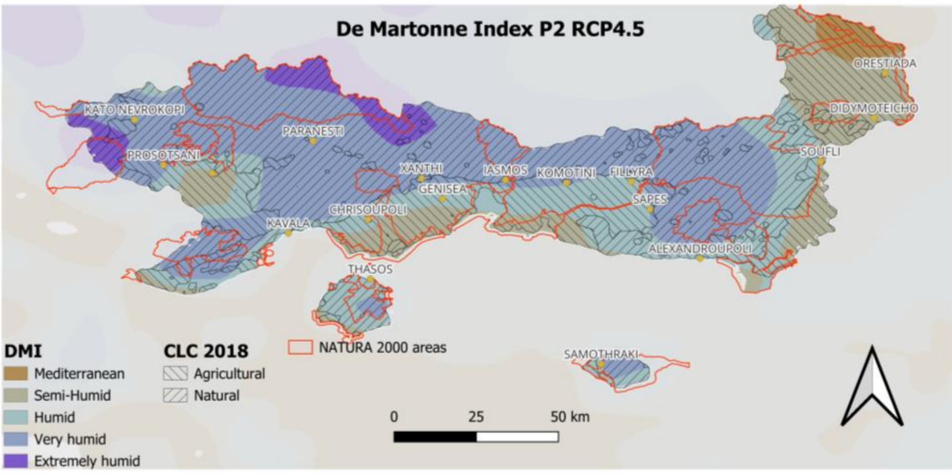

Figure 5. De Martonne Index spatial distribution for the time period 2070–2100 under the RCP4.5 scenario.

The alteration of the study area's bioclimate towards warmer and drier conditions is more evident at the first period of the RCP8.5 (Figure **Error! Reference source not found.**). Under the high-emissions global warming scenario, the expansion of the agricultural areas impacted by the

Mediterranean (from 1.1% in the Ref to 3.5% in P1 RCP8.5, Figure **Error! Reference source not found.**) and the Semi-humid regimes (from 12.6% to 21.2%, Figure **Error! Reference source not found.**) may increase the cropland demanding supplementary irrigation in the near future. Concomitantly, the more humid bioclimates (Extremely humid, Humid, Very humid) are spatially decreased with the Extremely humid class appearing as mostly limited (from 11% in the Ref to 3.7% in P1 RCP8.5, Figure **Error! Reference source not found.**), impacting on the northern and western natural landscapes' water needs.

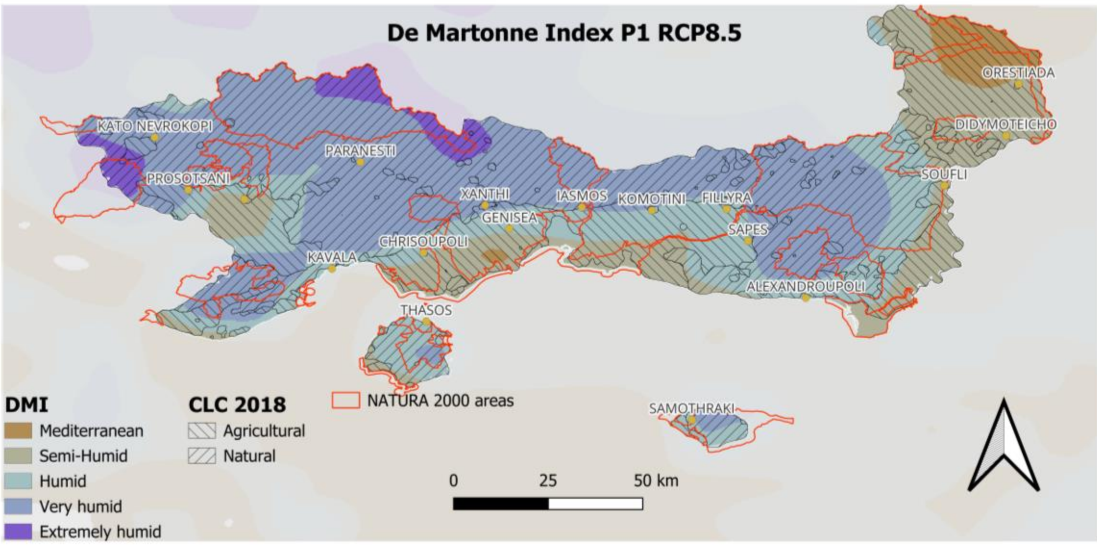

Figure 6. De Martonne Index spatial distribution for the time period 2030–2060 under the RCP8.5 scenario.

Results on the future long-term time frame (2070–2100) under the extreme RCP8.5 scenario depict a profound xerothermic trend since a significant spreading of the Mediterranean climate category is projected to occur over the western, southern and eastern agricultural landscapes and lowlands (Figure **Error! Reference source not found.**). This future evolution is demonstrated by the more than 5-fold and 20-fold spatial distribution of the Mediterranean conditions compared, respectively, to the P1 RCP8.5 (from 3.5% to 19.8%, Figure **Error! Reference source not found.**) and to the Ref (from 1.1% to 19.8%, Figure **Error! Reference source not found.**). Such projections highlight the increase of the agricultural land foreseen to be affected by these more xerothermic conditions (to 40.1% in total for both the Mediterranean and Semi-humid classes, Figure **Error! Reference source not found.**). As conditions become drier and warmer, the necessity for supplementing the crops' water requirements becomes more evident.

On the other hand, a notable expense of the Very humid (from 51.3% in the Ref to 48% in P1 RCP8.5 and 27.6% in P2 RCP8.5, Figure **Error! Reference source not found.**) and an absence of the Extremely humid bioclimate (from 11% to 3.7% in P1 RCP8.5 and 0% in P2 RCP8.5, Figure **Error! Reference source not found.**) are expected to characterize the natural areas of the EMTh. This probable further limitation of the more humid environments' distribution indicates the forming of climatically stressed natural areas (i.e., forests, wetlands) in the EMTh.

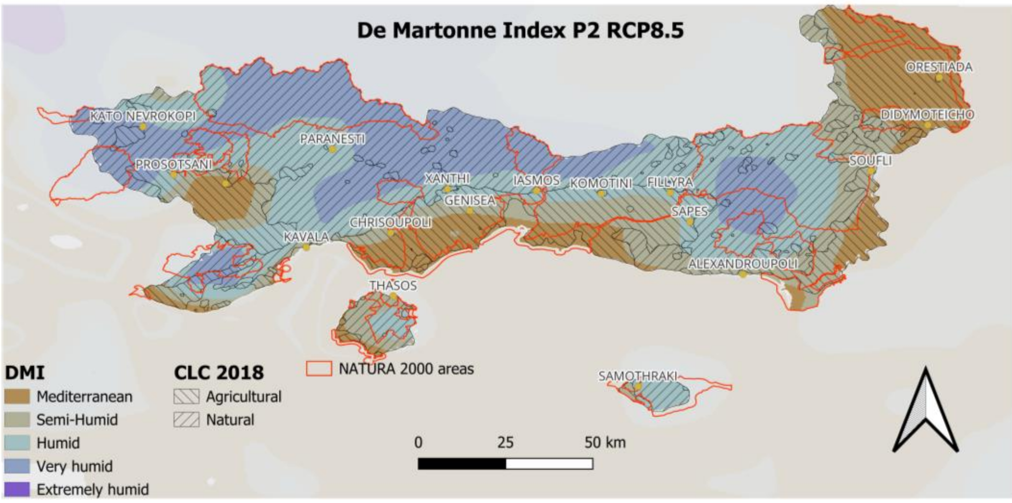

Figure 7. De Martonne Index spatial distribution for the time period 2070–2100 under the RCP8.5 scenario.

Overall, as shown in Figure **Error! Reference source not found.**, the summarized percentage area distribution demonstrates the predominance over the EMTh of the Humid and Very humid categories in all examined cases (e.g., 75.4% in total for the Ref, 74.4% for P2 RCP 4.5 and 59.9% for P2 RCP 8.5). Nevertheless, two major trends are evidenced, which underline the warming and drying of the natural and agricultural areas under both emission scenarios (RCP 4.5 and RCP 8.5).

Firstly, a continuous spatiotemporal limitation especially of the Very humid conditions (from 51.3% in the Ref to 49.9% in P2 RCP 4.5 and 27.6% in P2 RCP 8.5) and of the Extremely humid conditions (from 11.0% in the Ref to 4.6% in P2 RCP 4.5 and 0% in P2 RCP 8.5) is projected to take place over the natural landscapes of higher elevations (Figures 3, 5 and 7).

Secondly, a spatiotemporal increase, particularly of the Mediterranean bioclimatic conditions (from 1.1% in the Ref to 2.1% in P2 RCP 4.5 and 19.8% in P2 RCP 8.5) and of the Semi-humid conditions (from 12.6% in the Ref to 18.9% in P2 RCP 4.5 and 20.3% in P2 RCP 8.5) is expected to influence the lowland agricultural areas (Figures **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.**) of the EMTh.

By considering the above outcomes, it is apparent that profound changes (both percentage area limitations and increases) result for the second time-period of the extreme RCP8.5 scenario. It is estimated that by 2100, the more xerothermal conditions (both Mediterranean and Semi-humid) will account for the remarkable 40.1% of the EMTh consisting majorly of agricultural areas (Figure **Error! Reference source not found.**) that will depend on supplementary irrigation. At the same time, the more spatially limited Very humid conditions will inflict pressure on the natural areas (Figure **Error! Reference source not found.**), accounting for 27.6% of the EMTh.

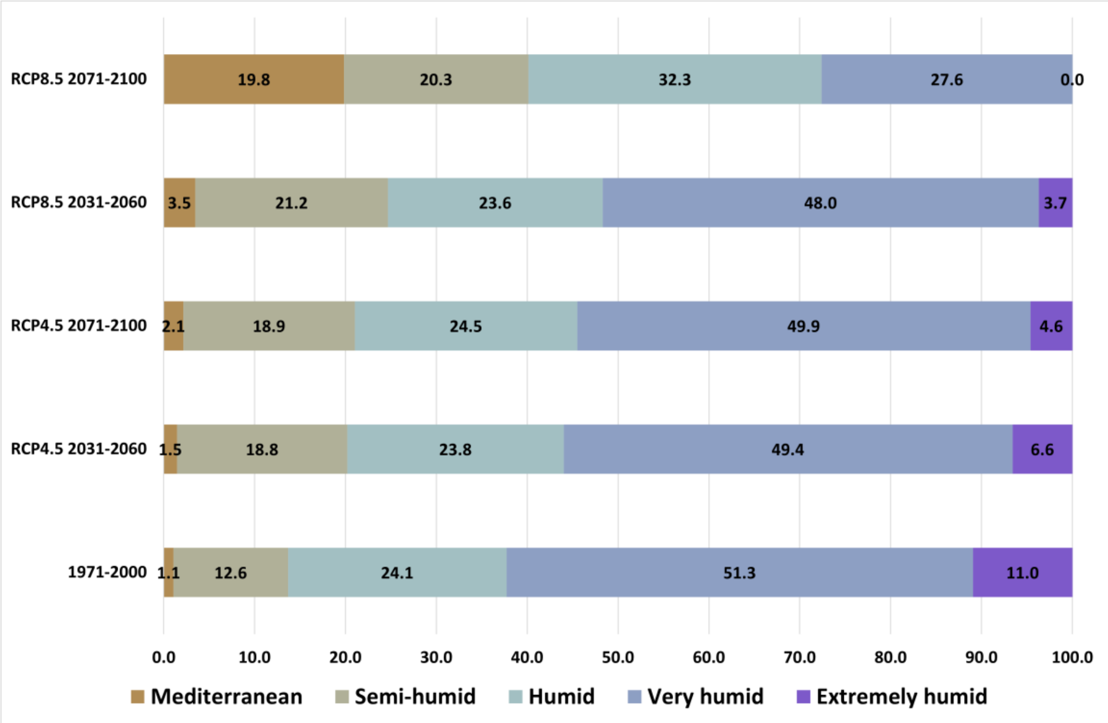

Figure 8. De Martonne Index spatial statistics per class, period, and emission scenario.

In their recent bioclimatic study over the entire Southeastern European territory, Charalampopoulos et al. [19] have exploited the DMI classification for the 1981–2010 reference period and three consecutive timeframes (2011–2040; 2041–2070; 2071–2100), under the RCP7 and RCP8.5 emission scenarios. By performing comparisons between periods, the authors projected xerothermic trends over the present study's area of interest (EMTh). The transition in the direction of a warmer and drier regime was prominently demonstrated for the long-term period of the extreme RCP8.5 where the expected significant expansion of the areas with the Mediterranean and majorly the Semi-dry climates were captured mostly in the southern parts of the EMTh.

3.2. The Spatial Distribution of the Emberger Index (EI)

The illustrated classification (Figure 9) demonstrates the bioclimate types of characterization by three (3) main classes of the Q (Humid; Sub-humid, Semi-arid) combined with three (3) temperature conditions m (Mild winter, Cool winter, Cold winter). These combinations result in seven (7) Q2 classes of the EI in total: Humid, Mild winter; Humid, Cool winter; Humid, Cold winter; Sub-humid, Mild winter; Sub-humid, Cool winter; Sub-humid, Cold winter and the Semi-arid coupled only with the Cold winter temperature conditions.

It is highlighted that the Q2 classes' presentation in the legends but not in the spatial distribution maps (e.g., Figure 9) and the percentage (%) relative surface per geographical zone chart (Figure 14) is attributed to the resulting classes' very limited (%) coverage values.

Overall, the outcomes on the geographical distribution of the above phytoclimates (Figures **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.** and 14) reveal the dominance of the Humid and Sub-humid (and to a much lesser extent of the Semi-arid) classes coupled with the Cold winter temperature conditions, which sum up to 68.3% of the EMTh area. These phytoclimates appear mostly over the natural landscapes of the EMTh except for some western and eastern parts which are dominated by agricultural lowlands. Also, a transition from the north to the south towards drier and warmer conditions is reflected by the appearance of the Humid, Sub-humid classes combined with the Cool winter regime (25.9% spatial distribution, Figure 14), and with the subsequent warmer Mild winter category (5.9%, Figure 14) shown for the

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lowland areas consisting of natural and agricultural landscapes along the sea coast and the natural formations of the Thasos and Samothraki Islands.

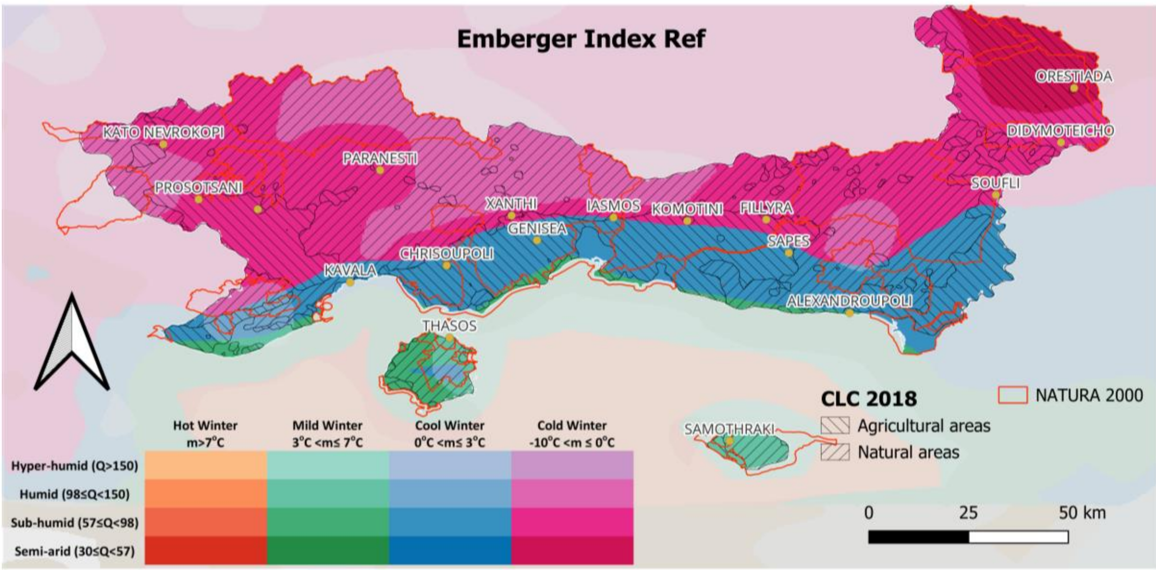

Figure 9. Emberger Index spatial distribution for the reference period (Ref: 1970–2000).

With respect to the Ref, the same phytoclimatic characterizations are evident for the examined area at the first period of the RCP4.5 scenario (Figure **Error! Reference source not found.**), along with the appearance (disappearance) for the first time of the Humid, Warm winter (Semi-arid, Cold winter) conditions mostly shown for the natural areas of Samothraki (northeastern agricultural areas). The remarkable xerothermic trend, already expected at this period, is demonstrated by the significant decreases of the natural areas affected majorly by the Humid and Sub-humid, Cold winter combinations (from 62.7% in the Ref to 28.1% in the P1 RCP4.5, Figure 14) in favor of the remarkable almost doubling of the areas consisting of natural and agricultural landscapes characterized by the leading Humid/Sub-humid, Cool winter phytoclimatic conditions (from 25.9% in the Ref to 53% in the P1 RCP4.5, Figure 14) and secondly, for the first time, by the Semi-arid, Cool winter conditions (from 0% in the Ref to 3.1% in the P1 RCP4.5, Figure 14). Distribution increases are also shown for the drier and warmer Humid/Sub-humid, Mild winter regimes (from totally 5.9% in the Ref to 15% in P1 RCP4.5, Figure 14), which are projected to influence the southern, mostly agricultural lowland coastline and approximately the whole of the natural landscaped Thasos and Northern Samothraki Islands. It is also notable that for the first time, although spatially very limited, even more xerothermic Humid, Warm winter conditions appear over these Islands (spatial coverage of 0.9%, Figure 14).

Distributions of the EI's classes at the second period of the RCP4.5 scenario (P2 RCP4.5) depict very small differentiations compared with the respected at the P1 RCP4.5 (Figure **Error! Reference source not found.** vs. Figure **Error! Reference source not found.**). The resulting xerothermic trend mostly refers to the natural areas' limited decrease characterized by the Humid, Cold winter bioclimate (from 12.7% in the P1 RCP4.5 to 10.9% in P2 RCP4.5, Figure 14) and by the Sub-humid, Cold winter bioclimate (from 15.4 % to 13.9%, Figure 14). Concomitantly, a slight expansion of the natural areas under the Sub-humid, Mild winter regime (from 12.2 % in the P1 RCP4.5 to 14.4% in P2 RCP4.5, Figure 14) and under the Humid, Cool winter conditions (from 6.7 % to 7.7%, Figure 14) is expected. Furthermore, a barely extended more xerothermic area of Sub-humid, Warm winter bioclimatic characteristics results, for the first time, over the southern part of Thasos Island (spatial distribution of 0.2%, Figures **Error! Reference source not found.** and 14).

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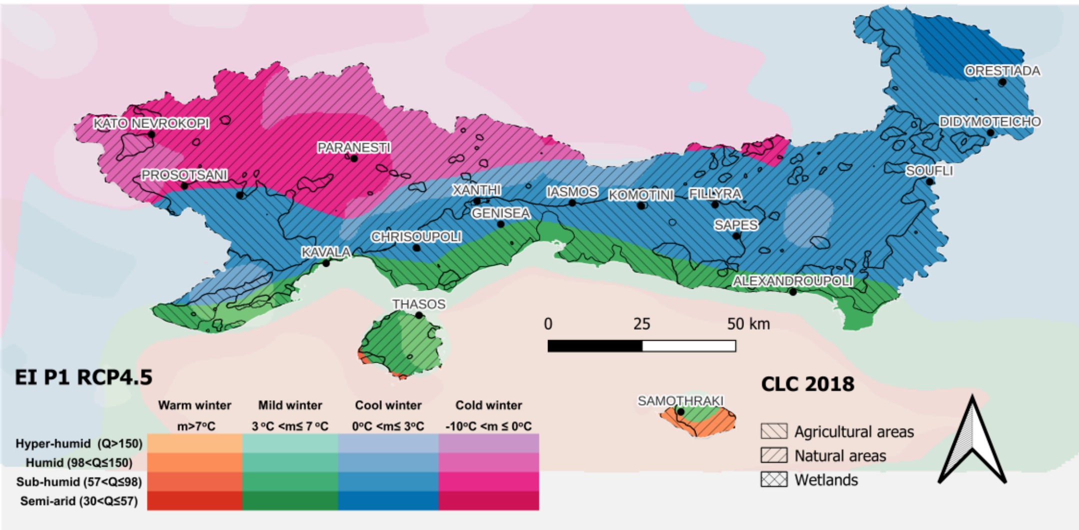

Figure 10. Emberger Index spatial distribution for the time period 2030–2060 under the RCP4.5 scenario.

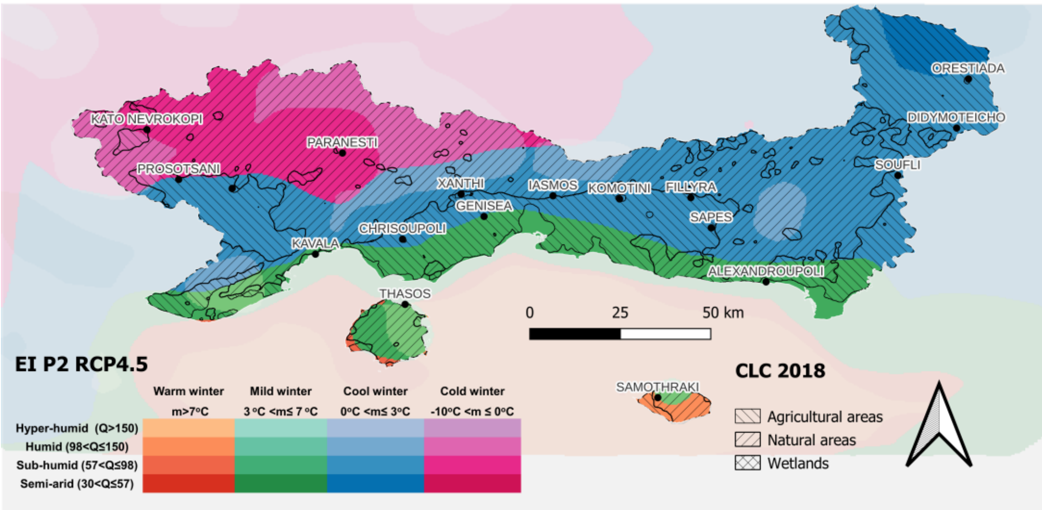

Figure 11. Emberger Index spatial distribution for the time period 2070–2100 under the RCP4.5 scenario.

Except for some slight differences with reference to the P2 RCP4.5 case, the distributions of the EI's classifications at the first period of the extreme RCP8.5 scenario (P1 RCP8.5) overall exhibit similar patterns (Figure **Error! Reference source not found.** vs. Figure **Error! Reference source not found.**). Compared with the respective P1 RCP4.5, lesser, mostly natural areas, are expected to fall within the Humid, Cold winter regime (from 21.4% in the Ref to 12.7% in P1 RCP4.5 vs. 9.4% in P1 RCP8.5, Figure 14). This is also shown for the agricultural areas under the Humid, Mild winter conditions (from 2.4% in the Ref to 2.8% in P1 RCP4.5 vs. 2% in the P1 RCP8.5, Figure 14).

On the other hand, few additional agricultural and natural surfaces are to be affected by the more xerothermic Semi-arid, Cool winter (0% in Ref to 3.1% in P1 RCP4.5 vs. 4.7% in P1 RCP8.5, Figure 14), the Sub-humid, Cool winter (24% in Ref to 46.3% in P1 RCP4.5 vs. 49.3% in P1 RCP8.5, Figure 14) and the Sub-humid, Mild winter regimes (from 3.5% in the Ref to 12.2% in P1 RCP4.5 vs. 13.5% in P1 RCP8.5, Figure 14).

Under the extreme RCP8.5, the phytoclimatic footprint of the EMTh appears as distinctly altered by the year 2100 (Figure **Error! Reference source not found.**). Outcomes exhibit the most intense xerothermic trends demonstrated by the significant expansion (up to more than ten-fold vs. the Ref) of both agricultural and natural areas characterized by the Sub-humid, Mild winter phytoclimate

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(from 3.5% in the Ref to 13.5% in P1 RCP8.5 and 41.8% in P2 RCP8.5, Figure 14) and the appearance, for the first time, of the Semi-arid, Mild winter over limited northeastern agricultural areas of the EMTh (distribution of 1.7%, Figure 14). The drier and warmer far future trend is also illustrated by the almost absent Humid, Cold Winter category (from 21.4% in Ref to 9.4% in P1 RCP8.5 and 0.3% in P2 RCP8.5, Figure 14) and the Sub-humid, Cold winter's spatial pattern severe limitation (from 41.3% in the Ref to 17.4% in P1 RCP8.5 and 10.5% in P2 RCP8.5, Figure 14) which appears concentrated over the northwestern natural areas. Finally, the intensity of the dry-thermal trend is underlined by the broader expansion of the areas with the Humid, Warm winter climate (from 0% in Ref to 0.8% in P1 RCP8.5 and 1.2% in P2 RCP8.5) and the Sub-humid, Warm winter climate (from 0% in Ref to 0.2% in P1 RCP8.5 and 3.7% in P2 RCP8.5) expected to influence the natural landscapes of the narrow southern coastline and of the islands of Thasos and Samothraki.

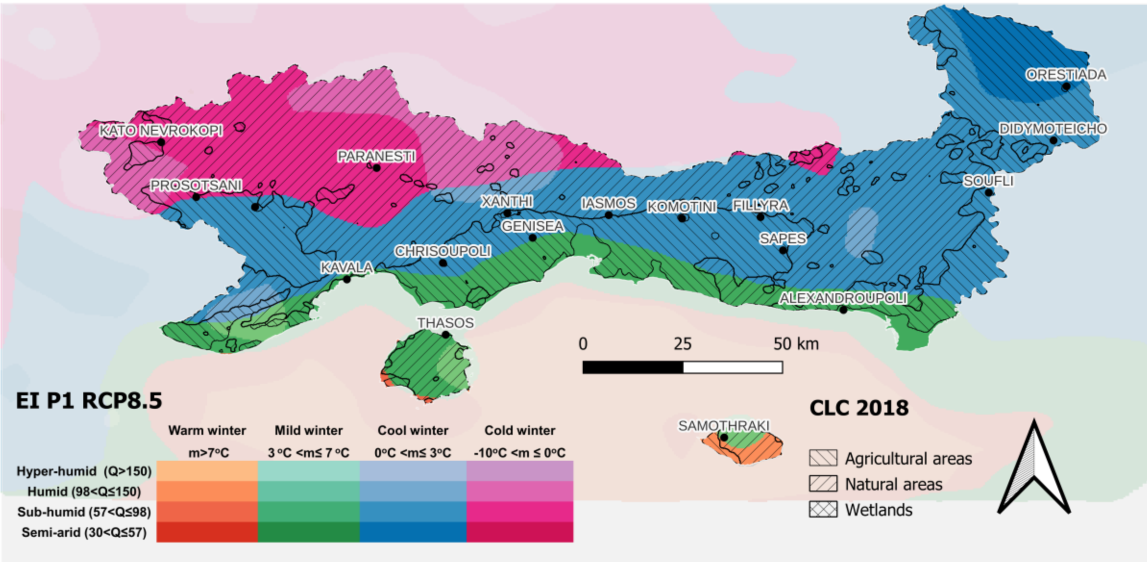

Figure 12. Emberger Index spatial distribution for the time period 2030–2060 under the RCP8.5 scenario.

The summarized distribution (% percentage area) presented in Figure 14 exhibits the prevalence of the Humid/Sub-humid/Semi-arid, Cold winter phytoclimatic categories only at the Ref (percentage spatial distribution of 68.3% in total), where most of the natural areas (Figure **Error! Reference source not found.**) fall within the Sub-humid, Cold winter category (41.3%).

The bioclimatic footprint of the EMTh is expected to be altered already at the P1 RCP4.5 where an overall xerothermic trend is demonstrated. The latter consists of the significant reduction mostly of the natural areas (Figure **Error! Reference source not found.**) under the abovementioned Cold winter combinations (from totally 68.3% in the Ref to 28.1% in P1 RCP4.5) and the concomitant notable expansion of the natural and agricultural areas affected by the Sub-humid, Cool winter climate regime (from 24% in the Ref to 46.3% in P1 RCP4.5) and by the Sub-humid, Mild winter (from 3.5% in the Ref to 12.2% in P1 RCP4.5).

Practically the same developments are estimated for the P2 RCP 4.5 with slight differentiations while similarities result between the P2 RCP4.5 and the P1 RCP8.5, highlighting the highly influential role of the latter most aggressive scenario. Thus, the percentage area decreasing under the Cold winter combinations (68.3% in Ref to 26.8% in P1 RCP8.5) vs. the increasing under the Cool winter combinations (25.9% in Ref to 56.7% in P1 RCP8.5) and Mild winter combinations (5.9% in Ref to 15.5% in P1 RCP8.5), are generally apparent.

The aforementioned trends are mostly intensified in the long term of RCP8.5. It is shown that the bulk of the natural and agricultural areas (Figure **Error! Reference source not found.**) are projected to be impacted by the more dry-thermal conditions corresponding to the Sub-humid, Mild winter class (spatial distribution of 41.8%) and secondly (32.6%) to the Sub-humid, Cool winter class.

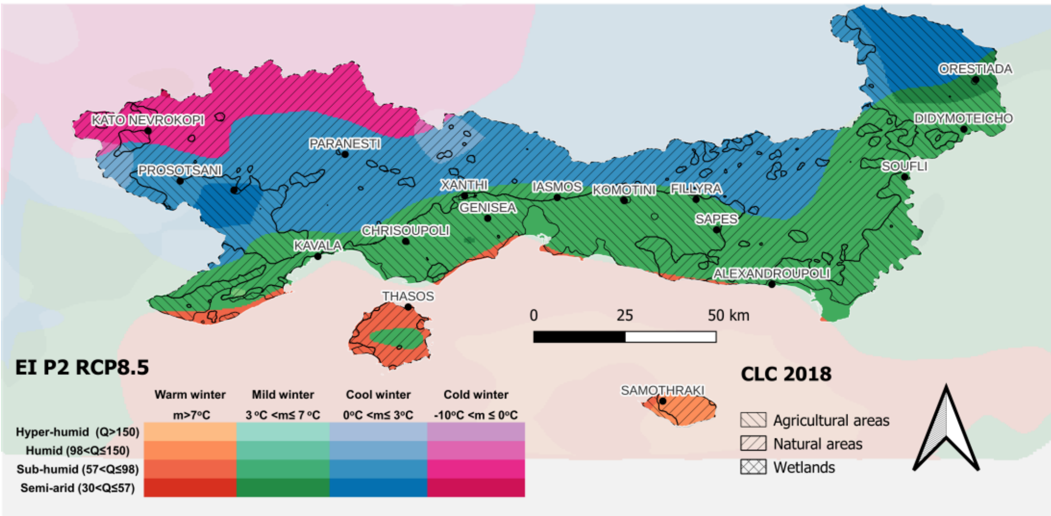

Figure 13. Emberger Index spatial distribution for the time period 2070–2100 under the RCP8.5 scenario.

Finally, the boosting of the bioclimatic change trend towards the warmer and drier conditions is evidenced by the appearance of the bioclimates with the Warm winter temperature characterization (4.9% in total) which are expected to affect the EMTh's natural and agricultural landscapes (Figure **Error! Reference source not found.**).

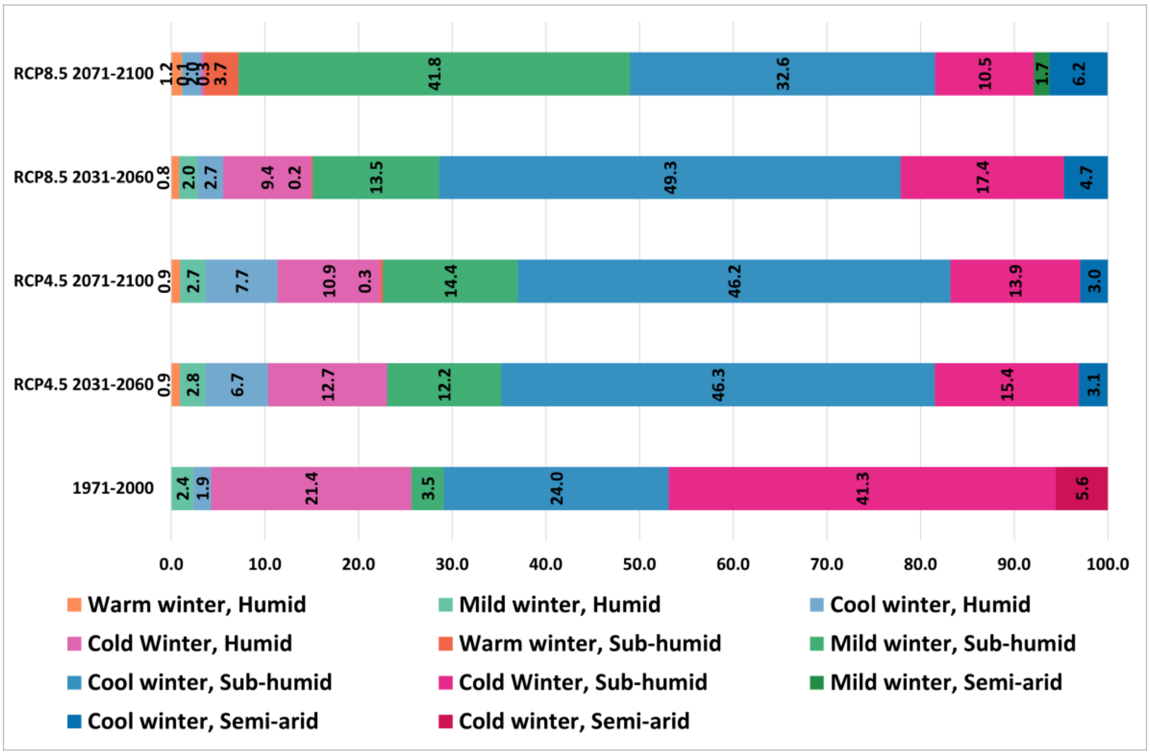

Figure 14. Emberger Index spatial statistics per class, period, and emission scenario.

The domination of the Sub-humid, Cold winter, and Humid, Cold winter climates over the investigated area at the reference period (1970–2000) has also been reported by Charalampopoulos et al. [18], who have conducted bioclimatic research over all phytogeographical regions of Greece. Their study demonstrated a xerothermic trend over the phytogeographic zone that included the EMTh region. Independently of the examined time periods (2021–2040; 2041–2060), a transition of the bioclimate characterized by the less dry-thermal conditions towards the more dry-thermal conditions is documented under both investigated emission scenarios (RCP4.5; RCP8.5). Similarly, as has been illustrated in the present study, the transition is mostly apparent at the second timeframe of the

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RCP8.5. More specifically, the authors have reported the occurrence in descending order of the more xerothermal Semi-arid, Temperate; Semi-arid, Cold; Semi-arid, Cool; Sub-humid, Cold and Sub-humid, Very Cold phytoclimates. Similarities between the two studies mainly include the existence of the Sub-humid, Cool winter and Sub-humid, Cold winter bioclimatic categories over a significant part located in the northern half of the EMTh.

3.3. Discussion

The study area (EMTh) represents a fairly large regional unit in Northeastern Greece, which is one of outstanding biodiversity and cultural interest [87]. The natural values and resources of the area are based on the fact that it is within both a transitional area between the temperate continental and the Mediterranean climate regimes and within a biogeographical crossroad between the southeastern Balkans and Anatolia [88,89]. The EMTh's natural capital importance is documented by the international interest for conservation and sustainable management, given that it hosts wetlands of global importance (Ramsar designations), transboundary river basins, and extensive natural/semi-natural forest lands under various forms of protection within protected area schemes [90,91]. Although the region encompasses extensive agricultural, livestock grazing areas and forestry (i.e., high value of provisioning ecosystem services), it has also developed an identity towards environmental conservation [90], promoting alternative developmental trajectories, including ecotourism [91–93](cultural ecosystem services). Thus, in this part of Northeastern Greece, the conservation and amelioration of these diverse and unique landscapes, taxonomic, functional and phylogenetic diverse flora (see e.g. [94]), the culturally important sites, and the unique wildlife, are essential attributes of management at the regional and the landscape scale, well documented also via relevant questionnaire surveys from the region [see e.g. [93]. Although the area is relatively well studied, particularly within some of its high-profile protected areas [88], research on the broader regional and climate-sensitive future planning is not well documented in the literature since most works are countered on particular ecosystem types [95,96] or on specific protected areas and species [97,98].

The EMTh shows pronounced local differentiations in climate as well as pronounced temporal variations in rainfall and other meteorological/weather conditions. These climatic conditions certainly affect vegetation and ecosystem types, land-use traditions, and many economic and cultural aspects. The results from this regional-level analysis demonstrate that significant changes on the landscapes will be driven by CC as predicted by the examined model-based indices.

Water availability is one out of many ecosystem services, and subsequently, land-use issues, that are expected to be severely affected. Climate-water impacts are rendered to affect ecosystem services of major environmental and well-being importance, including water cycle intensification, crop yield reduction, soil degradation, declining of water-related resources, and aquatic/riparian habitat degradation [99]. Water resources in Greece are particularly affected by climate extremes [100], with droughts, floods and soil erosion being also economically critical and thus constituting serious socioeconomic threats; these situations are commonly experienced in the EMTh, particularly in the large, transboundary Evros river basin [95]. Moreover, meteorological extremes in this part of the Balkans denote the incidence of extreme weather events and markedly the higher risk of landslides, particularly in high-relief landscapes lacking vegetation, as is the case following the occurrence of wildfires. Coastal environments are foreseen to be characterized by drier conditions, which may also be augmented by other complications, such as the inundation from coastal storms [96]. If the forecasts materialize in the near future, the biodiversity will suffer, and many studies already attribute CC to particular sensitive local species [97] and species assemblages, including aquatic biodiversity [101].

More frequent, more severe and more extensive wildfires (and megafires) constitute inevitable consequences of the climate crisis in the Mediterranean countries (see e.g.[102]), which appear as particularly serious in heavily forested regions, including the study area. The frequency of forest fires has increased in recent years owing mainly to record-breaking heatwaves [98]. An example of the catastrophic scale of mega-wildfires has been witnessed in August 2023, occurring also in protected areas within the broader investigated area. More specifically, the mega-fire in Evros burned more

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than 900 square kilometres, the largest wildfire ever recorded in the EU [103]. Yet the issue of fire regime management in the Mediterranean and in other warm temperate climate zones is particularly complex. Fire or so-called 'occupational burning' (agro-pastoral livestock grazing management) is not a misfortune, and the vegetation is well adapted to it. Insulating bark, easy sprouting, and fire-induced germination of seeds are responses of the resilient Mediterranean plants to fire [6]. In recent years, the widespread abandonment of traditional management practices in cultural and semi-natural upland landscapes has promoted larger wildfires, or mega-wildfires. So, fire regime management, especially within the agro-pastoral and agroforestry approaches, is mandatory [104]. Indispensable tactics involve efforts to assess, plan and prevent megafires [98] coupled with the knowledgeable exploitation of controlled fire regimes in association with megafaunal grazing in the Mediterranean climates [88].

The outcomes of the current study are closely correlated with the literature on several earlier works. The efforts to explore the predicted changes at both the regional and landscape scale may be particularly applicable for region-wide planning on CC adaptation and mitigation. In the last decades, a distinct aridity trend has been expanding northwards in the Mediterranean region [3], leading to heatwaves among other meteorological extremes.

Climate-threatened landscapes will not only burn rapidly and more frequently; they will permanently change their cultural landscape structure and character; their traditional cultural workings will alter. Landscape-level wholescale changes brought by mega-fires and increasing water stress are enough to create such step-changes. This will not only affect natural vegetation patterns but also impact areas of outstanding traditional and cultural formations. Currently, it is widely comprehended that cultural landscapes correspond to sites where anthropogenic activity is displayed through the historical transformation of nature. Developing the cultural landscape patterns and sustainability in an identifiable cultural landscape state is a time-consuming process [3,104,105]. Intricate and long-term nature–society dialectics are at play in these areas, especially in regionally biodiversity-rich areas such as the EMTh [88]. Agroforestry landscapes such as those in the Eastern Rhodope mountains are some of the best examples of long-lived resilient multifunctional bio-cultural landscapes [106], yet they are threatened by multiple changes both within and outside protected areas; ruderal plant taxa and communities of Greece [107] may find an opportunity to expand, threatening natural vegetation.

Conserving and restoring high-value sustainable landscape systems postulate the necessity for greater governmental initiatives and investments. The targeting of protected areas, despite great strides taken in several high-profile success stories, is inadequate for the conservation of the wider landscape values [93]. The regional and landscape perspectives are gaining interest [108], and, unfortunately, at the scale of both regional and landscapes frameworks, Greece seems to be poorly prepared in conservation planning [78,109]. Landscapes should be actively protected, yet very little effort is being made even within protected areas in Greece [88,93], where aesthetic degradation constitutes an important threat [110]. Also, there is evidence of poor stakeholder and societal participation within conservation initiatives, even for the protected areas belonging in the area of interest [111]. The issue of CC adaptation has recently developed, and few coordinated concrete actions have been implemented in the region [112]. Finally, other concerns involve the development of modern infrastructure, which may result in the fragmentation and degradation of natural landscape areas. In the EMTh, these projects include alternative energy resources (industrial windfarms and hydroelectric development in upland natural areas), water abstraction and storage constructions (dams, reservoirs), and antiflood river and torrent engineering works. In many cases, there has been conflict between these developments and landscape conservation objectives [93,113,114].

Predictions of future climate patterns are of paramount importance not only for land use planning and conservation practitioners, as well as for raising awareness of CC impact on the landscape, rural, natural and protected areas, that is currently really low [115]. Moreover, these well documented predictions are essential in the presence of complex long-term cultural relations with the landscape structure, which is also the case for the varied cultural landscapes of Northeastern

Greece that support numerous cultural ecosystem services (see e.g. [116]). Scientifically-driven and evidence-based approaches to adapting land use and landscapes features to mitigate undesired implications caused by CC are presently imperative; therefore, relevant initiatives should be developed within the area [96]. In this concept, decision-makers' assistance in choosing how to invest resources for applying conservation and adaptive planning is facilitated and encouraged in order to prevent the widespread damage as predicted to be induced by CC.

4. Conclusions

The study outcomes outline the bioclimatic change over the natural and agricultural landscapes of the Region of Eastern Macedonia and Thrace, Northeastern Greece. Thus, the present study's innovative findings resulting from the application of both bioclimatic indices (de Martonne index; Emberger index) may be summarized by the following major conclusions:

(a) Profound altered bioclimatic regimes predict trends towards more xerothermic environments under the two examined emission scenarios RCP4.5 and RCP8.5. Comparisons between the three study time frames (1971–2000; 2031- 2060; 2071–2100) highlight the temporal development in the direction of the more dry-thermal conditions, as predicted under both emission scenarios.

(b) Significant changes following the implementation of the de Martonne index concern the long-term timeframe of the extreme RCP8.5 scenario. Owing to high emission regimes and associated global warming by the end of the century, the more xerothermal Mediterranean and Semi-humid conditions will account for approximately 40% of the investigated area. The parts to be particularly influenced consist of the eastern, southern and western agricultural areas which are projected to require increased supplementary irrigation. Natural areas may also be increasingly stressed due to reduced humidity and precipitation regimes.

(c) As documented by the Emberger index, the spatiotemporal xerothermic evolution over the investigated area follows a North-South direction. An intensified xerothermic trend under the extreme RCP8.5 is also projected by the Emberger index, in the long run. By the year 2100, a substantial part of the natural and agricultural areas amounting up to nearly 42% is projected to be impacted by the Sub-humid, Mild winter conditions and up to nearly 33% by the Sub-humid, Cool winter conditions. The possible existence of the Warm winter combinations expected to impact on both agricultural and natural landscapes (distribution of nearly 5%) underlines the peaking of the bioclimatic shift towards warmer and drier conditions.

(d) Finally, a multi-scaled approach at the regional level should be helpful in planning for natural capital conservation, restoration and sustainability initiatives at the landscape level. This particular studied area is so diverse and complex and has several high-profile and well-studied protected natural areas or other designated areas of outstanding interest, both in its natural/semi-natural and cultural landscapes. However, new pressures from climate-associated stress may create severe problems associated primarily with water-related ecosystem services, i.e., water stress in agricultural and aquatic, wetland and riparian areas accompanied by wildfire frequence increase. Climate adaptation analysis would require a scientifically-informed and guided landscape approach and should not be relegated only to specific landscapes or high-profile protected areas as has already been done in some recent initiatives. Also, it is important to carefully assess where adaptation and mitigation measures may conflict with nature conservation initiatives. It is recommended that landscape-scale approaches should be taken in promoting climate adaptation and climate-smart planning initiatives throughout the Region of Eastern Macedonia and Thrace.

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