Tackling climate change impacts on biodiversity towards integrative conservation in Atlantic landscapes

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Tackling climate change impacts on biodiversity towards integrative conservation in Atlantic landscapes

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A R T I C L E I N F O

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A B S T R A C T

Throughout the last decades, the increasing pressure of anthropogenic (climate and land-use) changes has been a major impact on biodiversity in several regions and habitat types. These drivers have disturbed the timing of reproduction in animals and plants as well as the migration of animals resulting in changes in population size and species distribution. Our study analyses the impact of climate change in the spatial distribution of selected species, between historical period (1950–2018) and future period (2041–2070), in four case studies at a watershed level over the Atlantic region, highlighting the importance of integrating landscape trends to anticipate key biodiversity pattern responses. The results were compared to predicted future climate projections (2041–2070), based on two IPCC scenarios (RCP4.5 and RCP8.5), using a 5-model ensemble developed under the EURO-CORDEX project. Further, complementary downscaling methodologies were applied, allowing the increase of the spatial resolution from ~12 km to ~1 km in all climate variables. Land cover maps were developed using the Forecasting Landscape Scenarios Model. We assessed the impact of projected climate change and land cover development on specific vulnerable species distribution for each case study. The results showed an overall temperature increase for all case studies and both representative concentration pathways scenarios and a shift in potential habitat area of species addressed to areas upstream of the catchments. These predictions have a strong importance in defining conservation strategies of these vulnerable species, and may overall bring guidelines for the management of Atlantic landscapes in response to climate change, namely as pertinent ecological indicators under realistic future changing regional scenarios.

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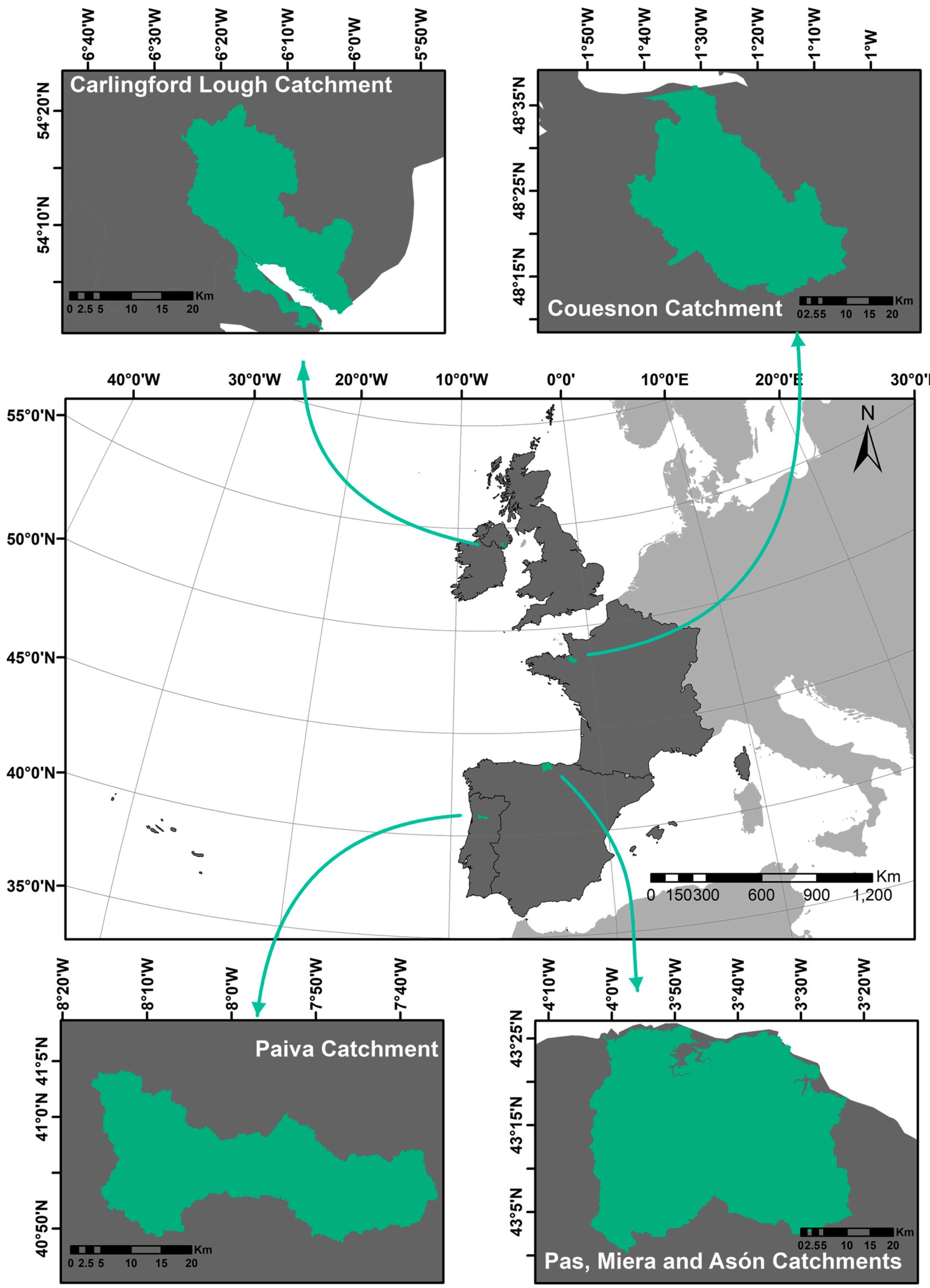

Fig. 1. Location of the four case studies; **a)** Northern Ireland / United Kingdom – Carlingford Lough catchment; **b)** France – Couesnon catchment; **c)** Portugal – Paiva catchment; **d)** Spain – Pas, Miera and Asón catchments.

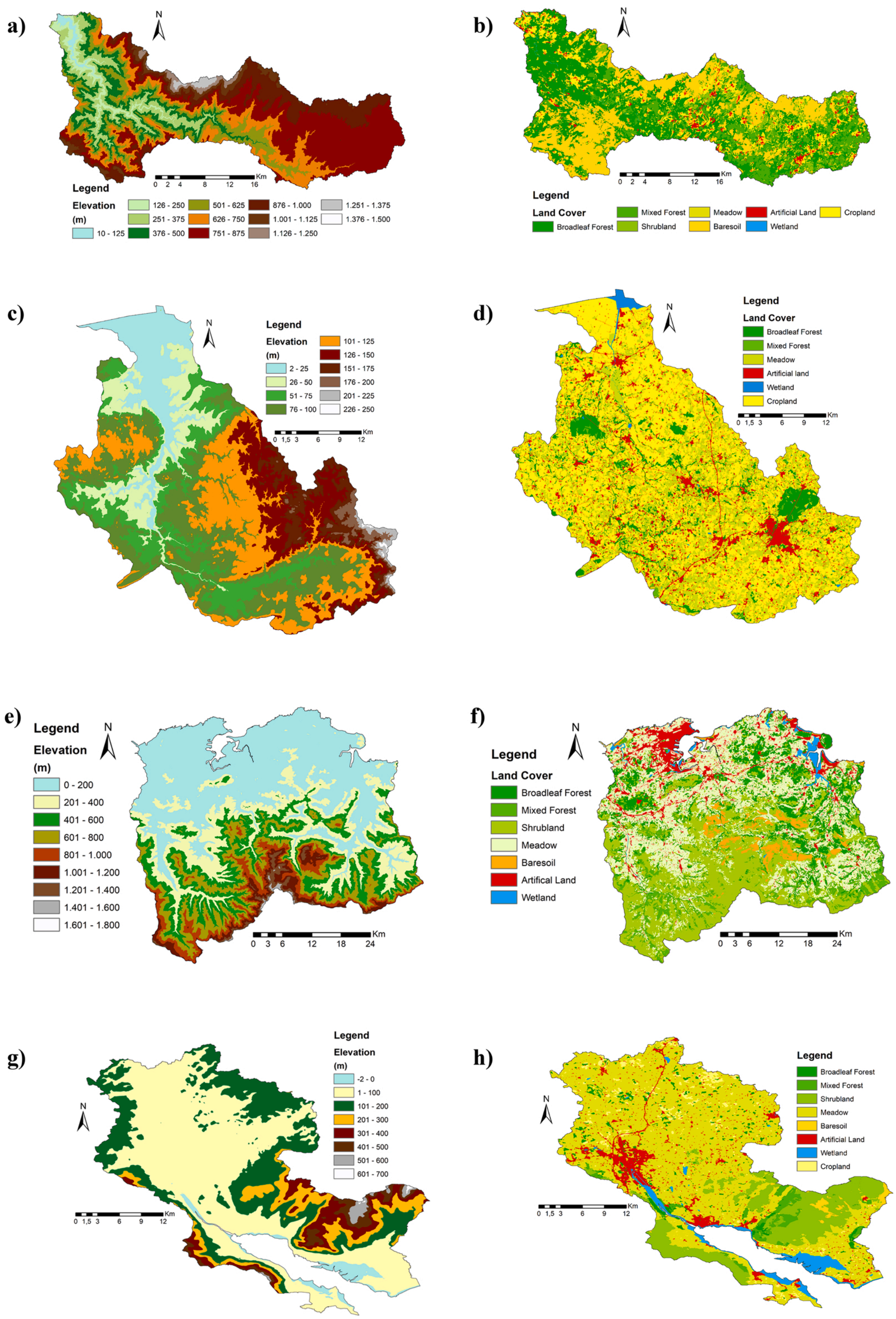

Fig. 2. Hypsometric of each case study catchment (left) and COS 2018 map (right); **a,b)** Portugal; **c,d)** France; **e,f)** Spain and **g,h)** Northern Ireland / United Kingdom.

1. Introduction

Climate change is a ubiquitous and growing global threat to biodiversity, ecosystems, and their services worldwide (Gaitán-Espitia and Hobday, 2021). Together with land-use changes, these are the most crucial factors that determine the distribution of species communities on Earth (Bertrand et al., 2011; Guisan and Thuiller, 2005; Lenoir et al., 2008). With the publication of the European Green Deal (EC 2019), 2030 Agenda for sustainable development (UN, 2015), and the 2030 EU Biodiversity Strategy (EC 2020), countries have now to fight climate change by adopting climate mitigation policies to reduce global greenhouse gas emissions and concentrations in the atmosphere to limit global warming. Also, will need to adopt measures and policies adapting to the consequences of climate change to make countries more resilient and less vulnerable to climate change effects.

Climate change is expected to cause a relative decline in some species and even their local or total extinction for the most vulnerable ones (Change, 2014). Among the expected consequences of climate change, some of the most critical are the predicted shifts in species geographic ranges and/or habitat suitability by the disruption of local biotic communities (Ashraf et al., 2016; Cobben et al., 2015; Fitzpatrick et al., 2008; Yi et al., 2016; Zhang et al., 2018). Species are expected to extend their ranges along the leading edge or contract along the trailing edge. This could result in increased competition, and for some species, overall population declines or extinction (Bellard et al., 2012). These shifts depend more on species mobility (Berg et al., 2010) and habitat fragmentation levels (Vos et al., 2008) rather than on species traits (Angert et al., 2011; MacLean and Beissinger, 2017), though traits can explain an uncertain amount of variation in range shifts (Buckley and Kingsolver, 2012).

Multiple examples are demonstrating how modifications in species distribution ranges may indicate early changes in their habitat distribution, including in the context of major global trends, such as those related with Amazonian rainforest, that are expected to be replaced on a large scale by tropical savannahs (Lapola et al. (2009), while Alpine and Boreal forests are likely to expand to higher altitudes shifting the tree line (Alo and Wang, 2008). This concerns also aquatic habitats. For instance, the combined effects of a decrease in rainfalls and an increase in temperatures may cause wetlands (i.e., lakes, ponds, streams, riparian ecosystems) to dry out (Diversity, 2009). Sustaining biodiversity in human-modified landscapes is therefore a key challenge due to constrained space for the establishment of new species population dynamics, namely in order to support land use planning and biological conservation (Wessely et al., 2017).

The Intergovernmental Panel on Climate Change (IPCC) predicts climate change to progressively intensify by the next mid-century. Climate is changing at an unparalleled rate, the average temperature which increased by 0.85 ºC in the last century, is projected to rise between 2.5 ºC (RCP4.5) and 4.3 C (RCP8.5) by the year 2100 (Change, 2014). For these reasons, actions required to prevent certain species from extinction ought to be taken before their distribution areas change irreversibly (ÖRÜCÜ, 2019) or determine newly suitable areas where species can thrive and assign conservation measures and management policies toward establishing new protected areas. Consequently, the identification of new spatial habitats and ecosystem vulnerability to global climate change and local stressors is an important step in the implementation and formulation of appropriate countermeasures. Several studies have previously demonstrated the potential impacts of climate change on species distribution (Beyer et al., 2021; Couet et al., 2022; Habibullah et al., 2022; Halsch et al., 2021; Manes et al., 2021; Orr et al., 2021; Trew and Maclean, 2021), although none used to high-resolution climate datasets.

Therefore, we propose a hierarchical modelling framework developed to address the influence of land use/cover attributes on the community-based local responses. In our proposal the effective use of these metrics will require the integration of pertinent characteristics of the landscape from finer scales, such as the change of climate conditions within the observed species habitats (listed in the IUCN red list), by developing different contrasting scenarios. The objectives of this study are threefold: (1) mapping current and projected future climate under two different Representative Concentration Pathway scenarios; (2) measuring current species habitat linked with historical climate conditions and (3) assessing how selective species ranges might change under future climate scenarios. Our analysis was based on four case studies (CS), characterized by human-activities that shaped landscapes, located in five countries (Portugal, Spain, France, Ireland, and the United Kingdom) along the Atlantic coast. This study is part of the ALICE Interreg Atlantic project (https://project-alice.com/).

2. Materials and methods

2.1. Study area

The four case study sites (Fig. 1) were chosen to address the common problems of natural resource management at a catchment scale in Atlantic landscapes, encompassing a large diversity of landscapes shaped by human activities.

The Portuguese case study is the Paiva river catchment (796 km^2). The Paiva River, considered to be one of the least disturbed rivers in Europe, is a medium-sized watercourse (nearly 115 km), located in northern Portugal, that drains into the highly regulated Douro river. Most of its catchment is subject to a temperate macro bioclimate, however, the estuary has a Mediterranean macro bioclimate. The catchment orography is complex, with the river source located approximately at 1000 m high, and the river mouth at 10 m height, comprising both gentle and very steep slopes (Fig. 2**a)**, mainly covered by forest (41 %) and pasture (38 %), followed by agricultural fields (13 %) (Fig. 2**b**).

The French case study is the Couesnon river catchment (1128 km^2), located in Northwestern France in the Armorican massif. The Couesnon River is 89 km long and discharges into the Bay of Mont-Saint-Michel (UNESCO world heritage site). It presents a quite simple orography, with a moderate top height (256 m) at the source (Fig. 2**c)**. This catchment is mostly composed of agriculture with mixed grazing pastures in the upper stream and polders at the interface with the sea (79.6 %), followed by artificial areas (7.5 %) and exceedingly small forest area (3.6 %) (Fig. 2**d**).

The Spanish case study site is composed of three neighboring river catchments Pas, Miera, and Asón located in Northern Spain. All of them are Atlantic catchments, draining into the Cantabrian Sea with a total drainage surface of 2047 km^2 and a total main river course of 223.9 km. All Spanish catchments (Pas, Miera, and Asón) were treated as a single catchment for this study. The orography of this case study is complex, with three different morphological sections that can be differentiated within each one of the catchments: (1) a coastal area with relatively soft slopes in the lower parts, (2) very mountainous middle internal valleys (elevations between 100 and 1200 m), and (3) highly mountainous range (maximum altitudes exceed 1700 m), with vertical slopes, in the upper lands (Fig. 2**e**). Within this site, shrublands (28.2 %) and meadows (26 %) cover most of the catchment's area, followed by forests (21 %) and wetlands (16.7 %) while artificial areas (5.3 %) represent a small portion of the catchment area (Fig. 2**f**).

The Irish Case study corresponds to the Carlingford Lough catchment. It is located on the East Coast of Ireland, across the border between Northern Ireland and the Republic of Ireland. The Lough is a coastal embayment extending 16.5 km into the Irish Sea, surrounded by mountains, on its northern shore by the Mourne Mountains in Northern Ireland, and on its southern shore by the Cooley Mountains in the Republic of Ireland. Even if the highest elevation in the catchment is observed in the southern part reaching 715 m, the catchment has a very uniform orography along the main river line that varies from 70 m elevation at the spring to 0 m at the mouth in the Irish Sea (Fig. 2**g**). Inflowing catchments drain an area of 475 km^2, with the majority lying within Northern Ireland (426 km^2). The land use is mainly comprised of meadows (58.8 %) and shrubland (15.4 %), followed by wetlands (10 %), artificial land (5.6 %), and forests (5.5 %) (Fig. 2**h**).

2.2. *Climate data*

To analyze the climate dynamics in each of the four case studies, historical maps (from 1950 to 2018) at a spatial resolution of ~1 km were produced for: mean (TG), minimum (TN), and maximum (TX) temperature and precipitation (RR). Different data sources were used depending on the case study. For the Portuguese case study, a previously developed high-resolution climate dataset, PT. HRES, was used (Fonseca and Santos, 2018). For the remaining case studies, the climate data (precipitation amount, and maximum, mean and minimum temperature at a ~10 km spatial resolution) were retrieved from the E-OBS v20e database (Cornes et al., 2018) and resampled to produce the targeted refined spatial resolution (~1 km spatial resolution). A statistical downscaling methodology was applied for temperatures (TG, TN, and TX) with the following exploratory variables: latitude, elevation, and Euclidean distance to the coastline. The statistical downscaling was performed with the Ordinary Least Squares (OLS) with yearly daily means. To obtain the final data, the daily anomalies were added to the estimated raster from the OLS. The obtained temperature database spans the period of 1950–2018. For precipitation, a simple bilinear interpolation was used to produce the ~1 km spatial resolution for all case studies, except for Spain, where the SPREAD dataset was used (Serrano-Notivoli et al., 2017).

Once retrieved the historical data, climatic datasets from a five-member ensemble of GCM-RCM chain simulations (Table 1), developed within the framework of the EURO-CORDEX project, were retrieved for the development of climate change projections for all case studies (http://www.euro-cordex.net/). Gridded daily precipitation total (RR), minimum (TN), and maximum (TX) 2-meter air temperatures were extracted for the future period of 2041–2070 over each study area, at a spatial resolution of 0.125º latitude × 0.125º longitude (~14 km × 11 km in the study area) and under RCP4.5 and RCP8.5 (Representative Concentration Pathways). The IPCC RCP scenarios represent a plausible baseline scenario (RCP4.5) that peaks around the year 2040 and carbon emissions stop increasing, while RCP8.5 represents the worst-case scenario where emissions continue to rise throughout the 21st century. The use of model ensembles is highly recommended to take due account the uncertainties associated with the design and parameterization of physical-mathematical climate models (Fonseca et al., 2020).

Regional Climate Models (RCMs) are coupled to Global Climate Models (GCM), which allows a significant reduction of scale and a consequent increase in spatial resolution of the study. These data were produced under the EURO-CORDEX project (1981–2100). The data were also subject to a bias correction performed under the previous project (SMHI-DBS45-MESAN, 1989–2010). The original spatial resolution is about 12 km (EUR-11, 0.11° latitude × longitude) in a round Gaussian mesh. Data were then interpolated to a regular mesh over each region under study by the bilinear interpolation. Complementary downscaling methodologies were applied, which allowed the increase of the spatial resolution from ~ 12 km to ~ 1 km in all variables (TG, TN, TX, and RR). Further, bias correction was performed for each coupled model, by subtracting/dividing (temperature/precipitation) the data from 2041 to 2070–1981–2010 and adding/multiplying (temperature/precipitation) to the historical data for the same 1981–2010 period, to achieve the final datasets for all climate models (Fonseca and Santos, 2017, 2019).

Table 1
Listing of model pairs (GCM-RCM) used in ALICE.

GCM	RCM
CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4–8–17
CNRM-CERFACS-CNRM-CM5	SHMI-RCA4
MPI-M-MPI-ESM-LR	CLMcom-CCLM4–8–17
ICHEC-EC-EARTH	DMI-HIRHMA5
MPI-M-MPI-ESM-LR	SHMI-RCA4

2.3. Land cover maps

Archive programmed satellite data (Landsat and Sentinel) have been acquired to produce land cover (LC) maps at three different dates (1990s, 2000s, present) using supervised classification methods for each CS. In situ or photo-interpreted vegetation, sample points were used as independent training/validation points. To make all LC maps comparable while accounting for specificities of each site, an original approach consisted in improving outcomes throughout correcting inconsistent LC transitions from a date to another. To avoid a salt-and-pepper rendering inheriting from pixel-based classification, dominant LC classes have been assigned to landscape features (eg. plots, topographical uniform entities) available from freely available datasets. Even so, some misclassifications may

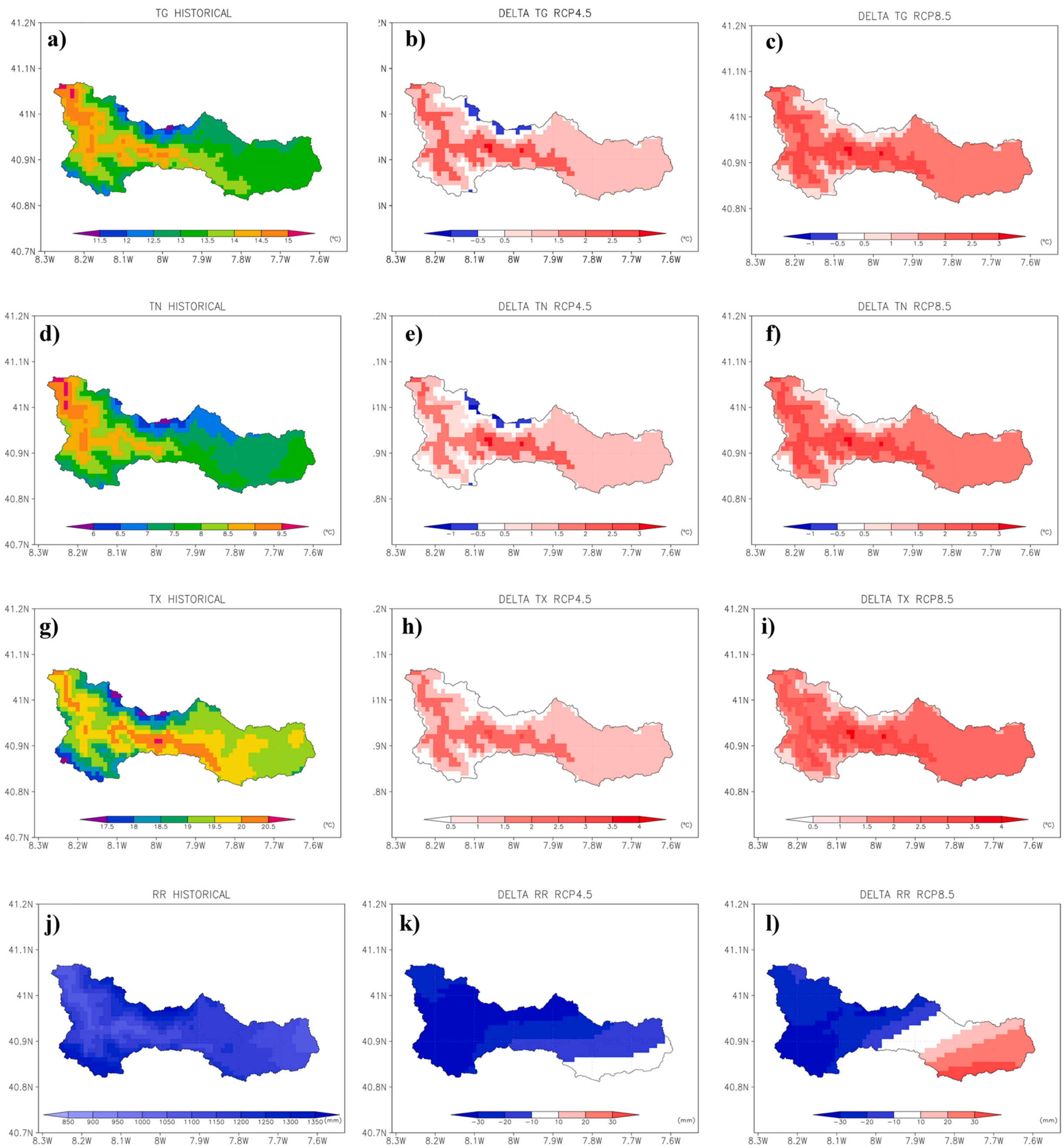

Fig. 3. Spatial distribution of climate variables in the Paiva catchment: **a)** annual mean temperature; **b)** mean temperature change under RCP4.5; **c)** mean temperature change under RCP8.5; **d)** annual minimum temperature; **e)** minimum temperature change under RCP4.5; **f)** minimum temperature change under RCP8.5; **g)** annual maximum temperature; **h)** maximum temperature change under RCP4.5; **i)** maximum temperature change under RCP8.5; **j)** mean annual precipitation; **k)** mean precipitation change under RCP4.5 and **l)** mean precipitation change under RCP8.5.

remain due to satellite images properties (date of acquisition, climate conditions) and related projected shadows of trees or hills in mountainous regions or early/late phenological states. Therefore, these inconsistencies have been removed by accounting for logical transitions rules to detect potential errors and correcting those LC maps exhibiting inconsistencies. LC classes were for all CS the following: broadleaf forest, mixed forest, meadows, artificial areas, water, and cultivated crops.

The FORecasting landscapE SCEnarios Model (FORESCEM) is used to spatially allocate futures LUCC based on narratives, defined throughout participatory or expert-based approaches, and to assess the combined effects of interactions between land use and land cover (LUCC) changes in anthropogenic landscapes (Houet et al., 2017). It aims to simulate LUCC at a fine scale, preserving landscape patterns i.e. it can simulate whether trends or contrasted LUCC. In this study, business-as-usual scenarios have been simulated based on a widely used Markov-chain approach (Mas et al., 2014), to obtain land cover maps for the year 2050.

2.4. Biodiversity data and habitat mapping

In this study, we analyze the biodiversity data at two levels: diversity (considering all species) and vulnerable species (focusing on

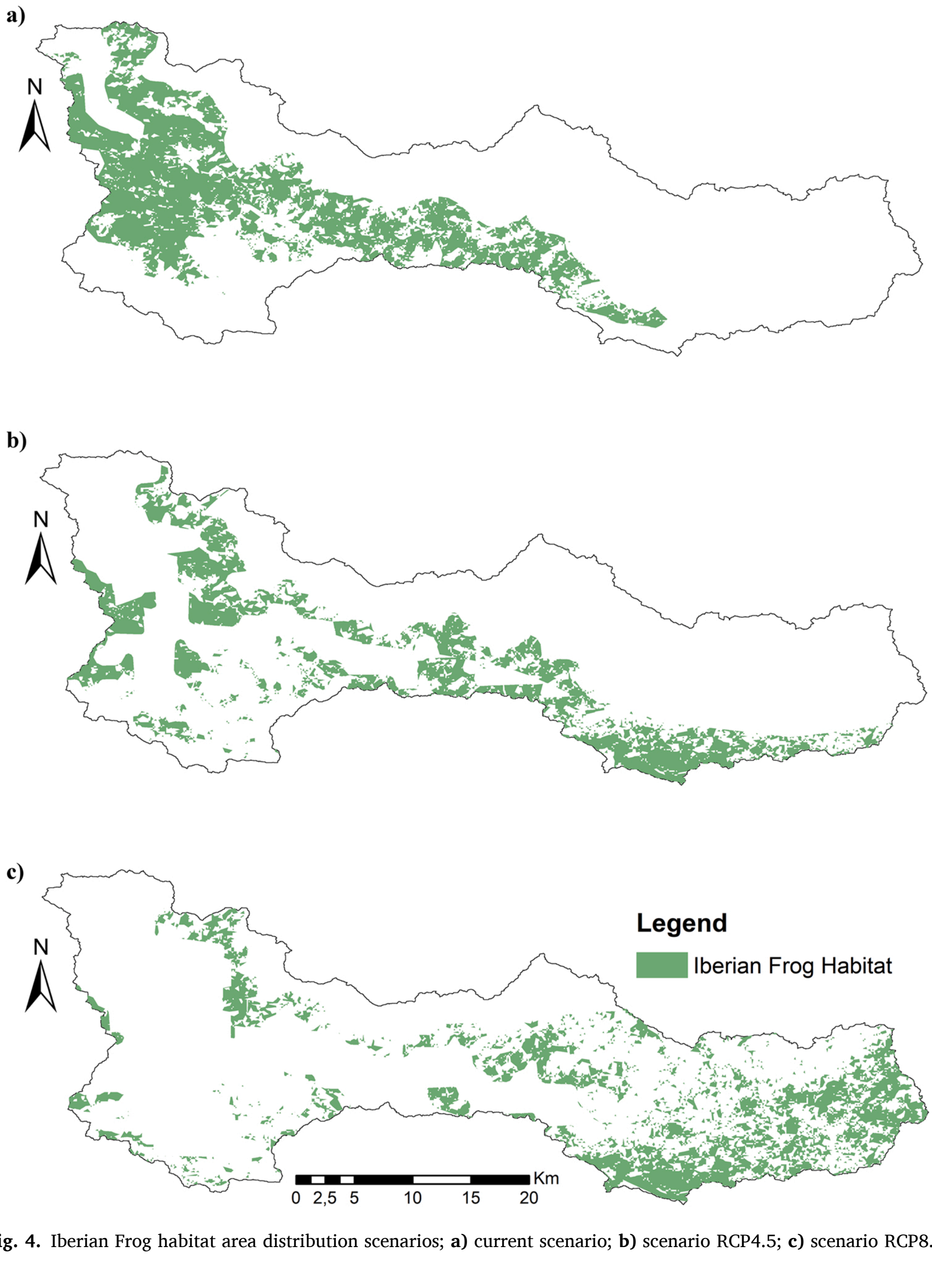

Fig. 4. Iberian Frog habitat area distribution scenarios; **a)** current scenario; **b)** scenario RCP4.5; **c)** scenario RCP8.5.

species with conservation issues). Biodiversity data for each case study were retrieved from the Global Biodiversity Information Facility database (GBIF – www.gbif.org)(GBIF.org, 2020a; GBIF.org, 2020b; GBIF.org, 2020c; GBIF.org, 2020d). GBIF is intended to provide open-access data concerning all types of life on Earth and it is funded by the world's governments. It provides researchers and institutions the necessary tools to enable them to share data in an open-access platform of where and when species have been recorded. A specific species was selected from the GBIF dataset for each case study, based on their extinction risk classification (only species with above vulnerable, or near threatened vulnerability status were selected) and subject to a shift in their natural habitat due to climate change impacts. The risk assessment of each species was derived from the International Union for Conservation of Nature's Red List of Threatened Species (IUCN; https://www.iucnredlist.org/) (Nature, 2001), which is a comprehensive information source on the global extinction risk status of animal, fungus, and plant species. For each species, we determine the favorable habitat based on land cover maps and the most probable temperature based on the spatial location of each sample from the GBIF database. Then, by combining

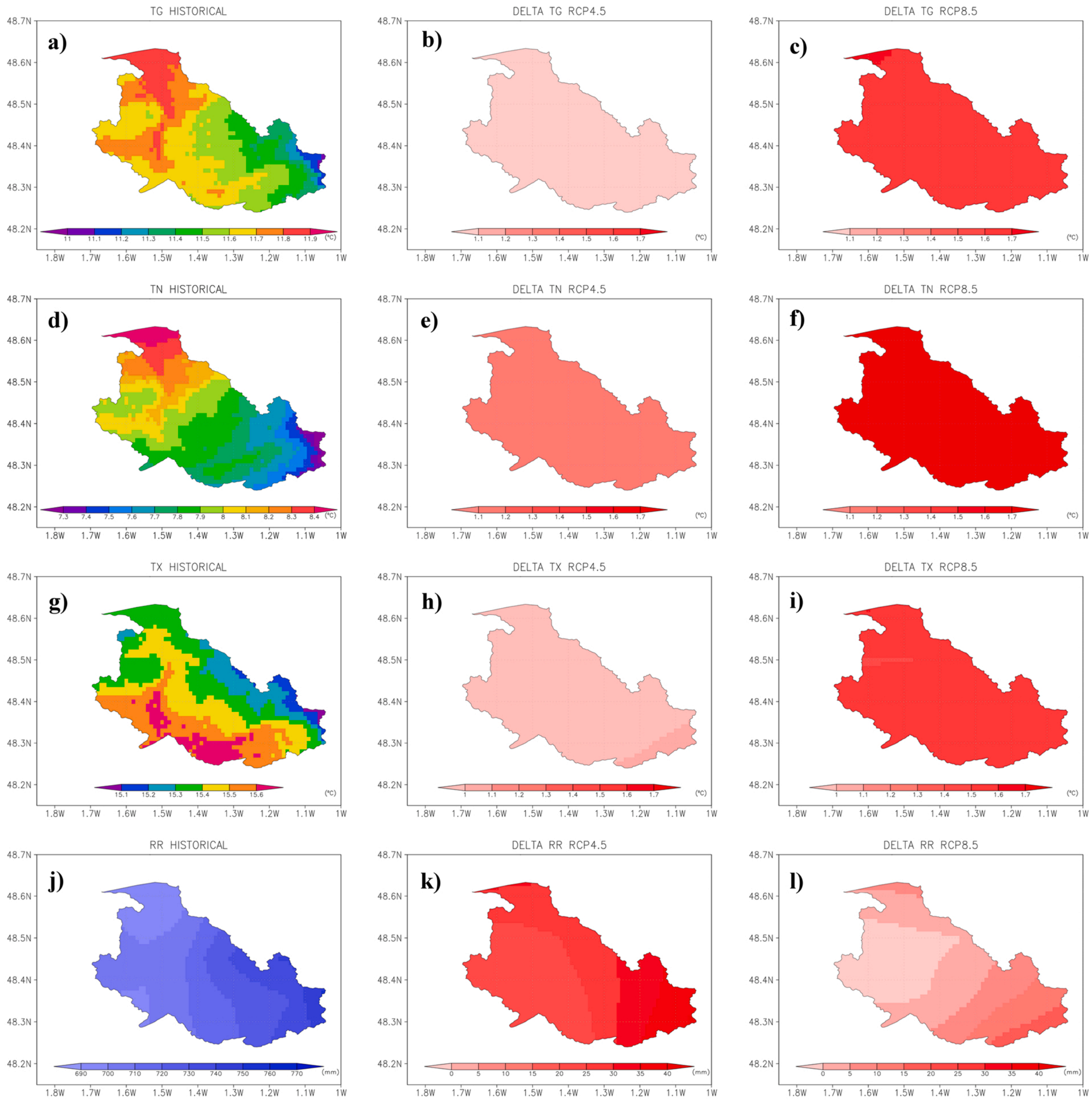

Fig. 5. Spatial distribution of climate variables in the France catchment: **a)** annual mean temperature; **b)** mean temperature change under RCP4.5; **c)** mean temperature change under RCP8.5; **d)** annual minimum temperature; **e)** minimum temperature change under RCP4.5; **f)** minimum temperature change under RCP8.5; **g)** annual maximum temperature; **h)** maximum temperature change under RCP4.5; **i)** maximum temperature change under RCP8.5; **j)** mean annual precipitation; **k)** mean precipitation change under RCP4.5 and **l)** mean precipitation change under RCP8.5.

these criteria with the developed future climate datasets, we identified areas where species natural habitat might be found in the future, and thus the possible future spatial distribution for each species. The approach followed in this study to determine habitat suitability was based on species information and species presence and absence (Brotons et al., 2004).

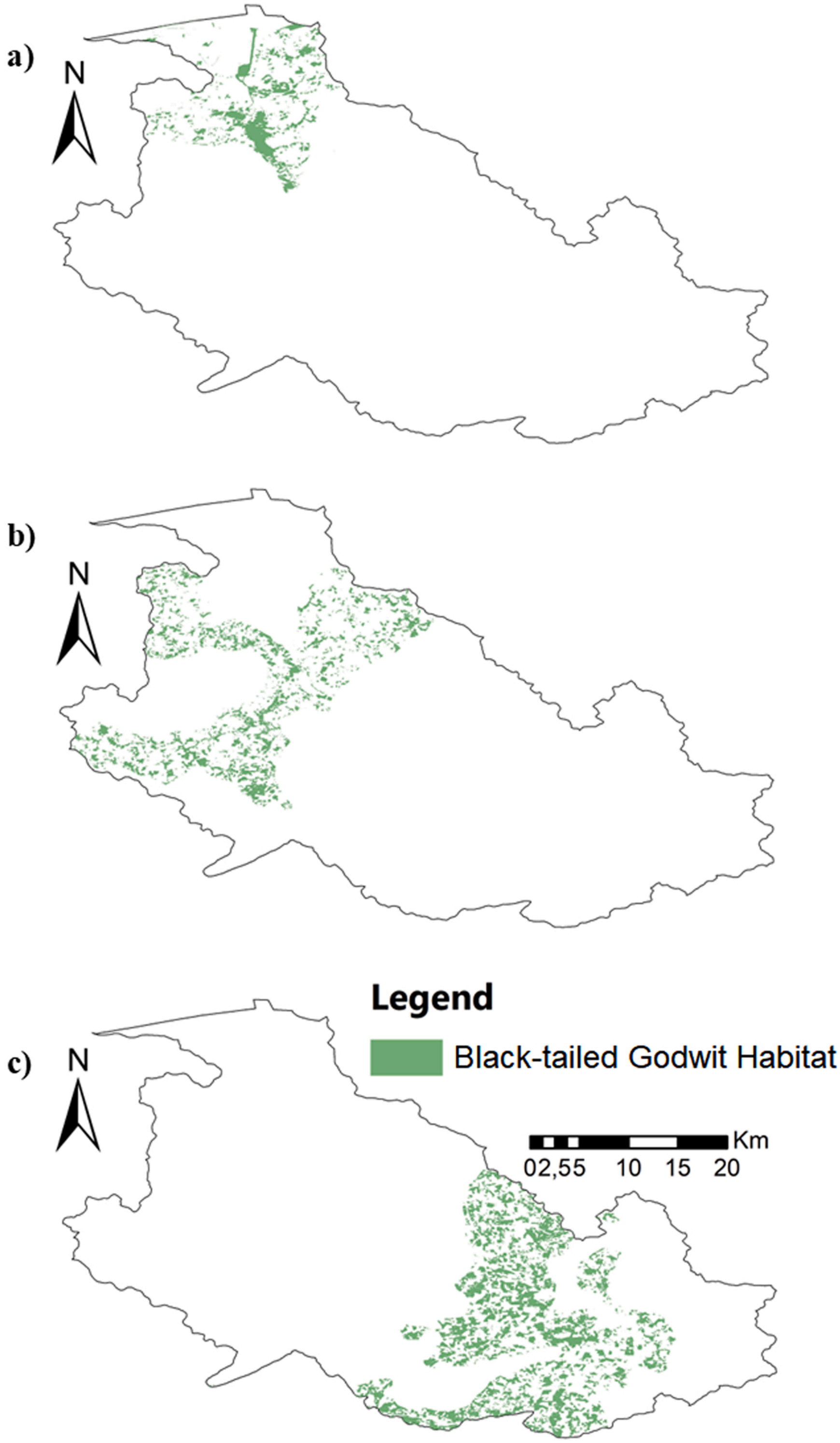

Fig. 6. Black-tailed Godwit habitat area distribution scenarios; **a)** current scenario; **b)** scenario RCP4.5; **c)** scenario RCP8.5.

3. Results and discussion

3.1. Portuguese case study

3.1.1. Climate characterization, current conditions, and change projections

The mean, minimum and maximum annual temperature and mean annual precipitation for the period 1950 – 2018 and the delta variation for both RCP4.5 and RCP8.5 are shown in Fig. 3**.** Paiva River showed higher TG along the river line (Fig. 3**a**), reaching values as high as 15.5 C, while lower temperatures were observed in the mountains north and south of the river (~11 C), as a result of elevation footprint (negative vertical temperature gradient). The same pattern was observed for both TN and TX (Fig. 3**d and g**). The projections for both RCP scenarios (for the period 2041 – 2070) showed a general increase of temperature for the entire region, where scenario RCP8.5 evidenced an increase for the entire catchment up to 2 C, 3 C, and 4 C for TG, TN, and TX, respectively.

Regarding the RR for the period 1950 – 2018 (Fig. 3**j**), it increased upstream the river (from 850 to 1200 mm) with higher precipitation in the mountains (1350 mm). The precipitation pattern also denoted the orography, due to the condensation barrier effect delineated by the mountains. Concerning the precipitation scenarios for the period 2041 – 2070 (Fig. 3**k and l**), there is a projected decrease in precipitation for scenario RCP4.5 of approximately 30 mm in the western part of the catchment, while in RCP8.5 there is an observed increase in precipitation in the eastern part of the catchment, varying from −30 to 30 mm.

3.1.2. Habitat mapping

There is widespread concern about a global decline in amphibian populations (Houlahan et al., 2000). Climate change is expected to substantially affect amphibians (Pounds 2001) and produce a shift in organisms dispersal (Araújo et al., 2006) The Iberian Frog (*Rana iberica*) is an endemic species in decline, listed as vulnerable in IUCN red list and EU Natural Habitats Directive (Evans, 2006). These species belong to the family *Ranidae* found only in Portugal and Spain. It is classified as vulnerable in the extinction risk level and its population is decreasing due to its short lifespan (2–3 years) and a continuing decline in area, extent, and or quality of habitat (forest and inland freshwater) (IUCN, 2021). Their main habitat is shores of clear streams, springs, and small rivers with running water, especially with riverside forests on their banks. The Iberian Frog population has declined by at least 30 % in the last ten years (Esteban, 2000; Malkmus, 2004). The main threats are mainly due to habitat loss through intensification of agriculture, tourism, urbanization, and alteration in the stream habitats resulting from forest exploitation (Jokimäki et al., 2005; IUCN, 2021). The current habitat of the Iberian Frog in the Paiva River catchment and potentially favorable habitats for scenarios RCP4.5 and RCP8.5 were mapped (Fig. 4).

3.2. French case study

3.2.1. Climate characterization, current conditions, and change projections

The mean temperature variation in the Couesnon catchment (Fig. 5) increased from the mouth to the spring, with higher temperatures along the main river line (11.9 C) and lower temperatures at higher altitudes (11 C) (Fig. 5**a**). Even though it, showed a very plain orography (<250 m), where the temperature profile lightly follows the relief, though the temperature is similar throughout the entire catchment area. The same behavior was observed for the TN (7.3 – 8.4 C) (Fig. 5**d**) and the TX (15.1 – 15.6 C) (Fig. 5**g**) profiles.

An increase of temperature is projected for all variables and it is similar for the RCP scenarios for the entire catchment: + 1.1 C and + 1.7 C for RCP4.5 and RCP8.5, respectively. Since the catchment shows a quite simple orography it is expected that the spatial variation temperature in the area remains uniform.

The historical RR (Fig. 5**j**) varied from 690 to 770 mm, where the highest one was observed in the small peaks present in the eastern part of the catchment and the lowest records were registered near the coast, following the orography footprint. Regarding the precipitation scenarios for the period 2041–2070 (Fig. 5**k and l**), there was a projected increase in precipitation of 25–40 mm in the catchment for scenario RCP4.5 with higher precipitation at higher elevations. For RCP8.5 the projected increase of precipitation was less pronounced (0–20 mm).

3.2.2. Habitat mapping

The Black-tailed Godwit (*Limosa limosa*) is a bird with a classification of near threatened in the IUCN Red List of Threatened Species, with a decreasing trend in population. The global population trend is declining at a rate of approximately 23 % over the last 25 years, though in Europe the population size is estimated to be decreasing between 30 % and 49 % over the same 25-year period (International, 2015).

It is usually found in grassland and Marine neritic and intertidal zones and, to some extent in artificial terrestrial areas (del Hoyo et al., 1996). This species is extremely sociable and migrates on a large front, traveling long distances between breeding and wintering areas (Gunnarsson et al., 2006). The major threats account for agricultural intensification and wetland drainage leading to loss of nesting habitat (Kentie et al., 2013; Lourenço and Piersma, 2008). Also, a considerable decline in spring floods, as a result of climate change, highlights the negative impact of agricultural abandonment and set-aside (Mischenko et al., 2019). Based on these facts, the current and projected habitat mapping of this species was determined (Fig. 6).

3.3. Spanish case study

3.3.1. Climate characterization, current conditions, and change projections

The temperatures in the catchment showed a longitudinal pattern that correlates with the orography, decreasing with the increase in elevation (Fig. 7). Higher TG was observed near the coastline (12 C) and can be as low as 6 C in the high mountains to the south (Fig. 7**a**). A similar pattern was observed for TN (Fig. 7**d**) ranging from 3.5 C to 8 C and for TX between 15 C and 18.5 C (Fig. 7**g**). An increase of temperature was projected for all variables and RCP scenarios for the entire catchment with higher altitudes showing the most significant increase, +1.7 C for TG and TN and +1.8 C for TX in RCP8.5.

The historical mean annual precipitation (Fig. 7**j**) varied from 1100 to 2500 mm. The highest value was observed in the high peaks of the catchment following the orography footprint. Regarding the precipitation scenarios for the period 2041–2070 (Fig. 7**k and l**), a spatially uniform increase in precipitation of 5–15 mm was expected in the catchment for scenario RCP4.5, while in RCP8.5 there was a projected decrease of precipitation more pronounced in the mountains (−200 mm) following an orographic pattern until the coast with a decrease of −5 mm in precipitation.

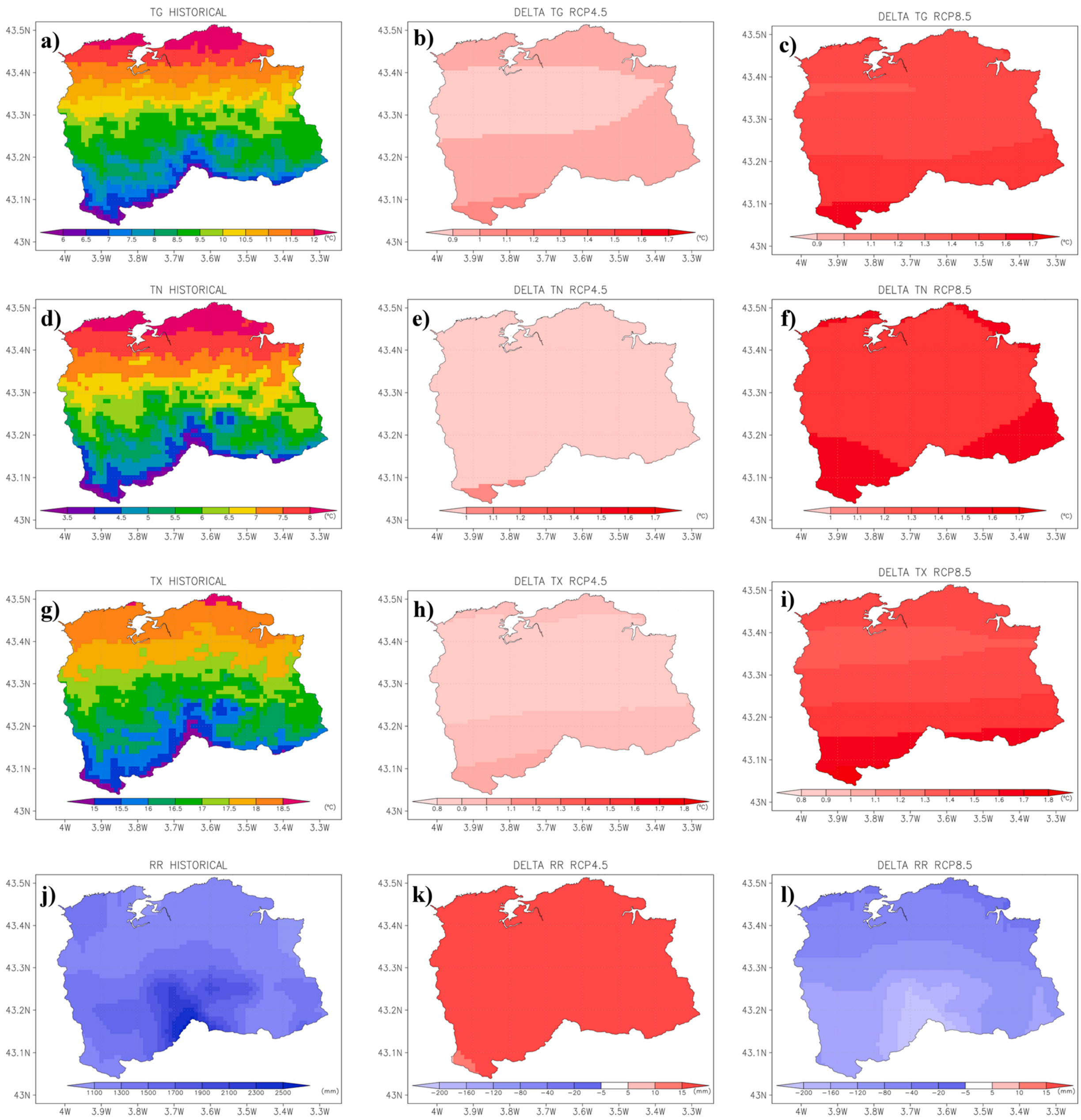

Fig. 7. Spatial distribution of climate variables in the Spain catchment: **a)** annual mean temperature; **b)** mean temperature change under RCP4.5; **c)** mean temperature change under RCP8.5; **d)** annual minimum temperature; **e)** minimum temperature change under RCP4.5; **f)** minimum temperature change under RCP8.5; **g)** annual maximum temperature; **h)** maximum temperature change under RCP4.5; **i)** maximum temperature change under RCP8.5; **j)** mean annual precipitation; **k)** mean precipitation change under RCP4.5 and **l)** mean precipitation change under RCP8.5.

3.3.2. Habitat mapping

The Spanish Fir (*Abies pinsapo*) native to Spain and northern Morocco, is an evergreen conifer that is classified as an endangered species with a decreasing trend in population. It usually thrives at higher altitudes (1400–1800 m) but can be found below 900 m mixed with communities of oaks and pines. The major threat of this species is fire, while pests and diseases also affect their growth especially during drought years which are more common with the present warming trend (Esteban et al., 2010; Linares et al., 2009). Taking into consideration its habitat (forest) and the current temperature range recorded in the GBIF sample's locations, the current and projected habitat mapping of this species was determined (Fig. 8).

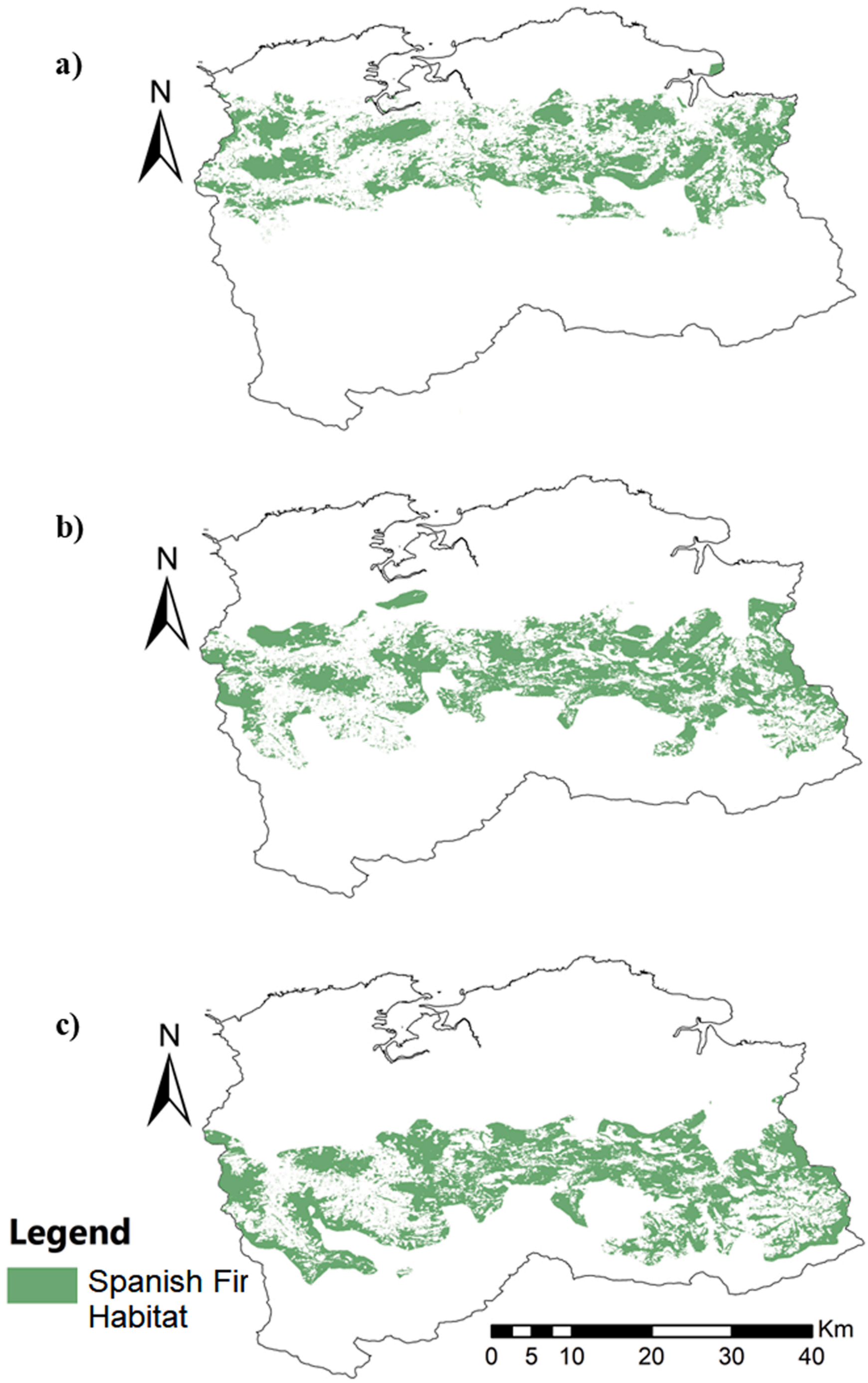

Fig. 8. Spanish Fir habitat area distribution scenarios; **a)** current scenario; **b)** scenario RCP4.5; **c)** scenario RCP8.5.

3.4. Northern Ireland / Republic of Ireland case study

3.4.1. Climate characterization, current conditions, and change projections

The TG, TN, TX, and RR for the historical period and the delta variation for both RCP4.5 and RCP8.5 in the Carlingford Lough catchment are shown in Fig. 9**.** The simple orography of the catchment (<100 m in the watercourse) denoted a simple temperature pattern for all variables (TG, TN, and TX), with lower temperatures observed upstream (4.5 C, 3 C, and 7 C, respectively) and higher temperatures (9.5 C, 6 C, and 13 C, respectively) on the small hills (600–700 m altitude) near the coast (Fig. 9**a, d and g**). The projections for both RCP scenarios showed an overall increase of temperature for the entire region and for all temperature variables, where RCP8.5 scenario showed an increase of temperature for the entire catchment up to 1.5 C, 1.6 C, and 1.5 C for TG, TN, and TX, respectively, more noticeable near the coast.

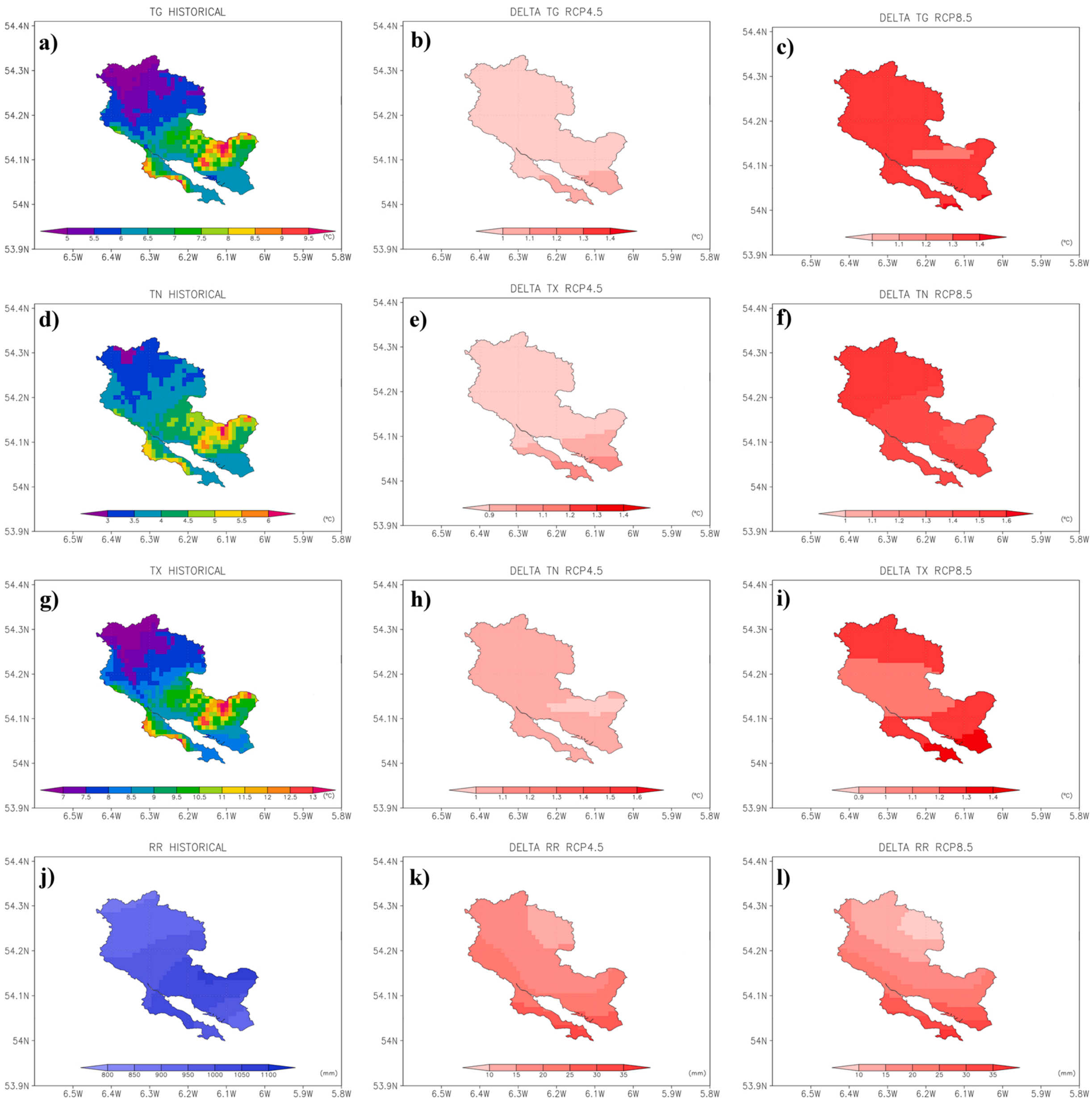

Fig. 9. Spatial distribution of climate variables in the Northern Ireland / United Kingdom catchment: **a)** annual mean temperature; **b)** mean temperature change under RCP4.5; **c)** mean temperature change under RCP8.5; **d)** annual minimum temperature; **e)** minimum temperature change under RCP4.5; **f)** minimum temperature change under RCP8.5; **g)** annual maximum temperature; **h)** maximum temperature change under RCP4.5; i) maximum temperature change under RCP8.5; **j)** mean annual precipitation; **k)** mean precipitation change under RCP4.5 and **l)** mean precipitation change under RCP8.5.

The RR (Fig. 9**j**) varied between 800 and 1100 mm with higher precipitation observed near the hills in the southeastern part of the catchment (orography dependent). The precipitation pattern also showed a decrease of intensity as we move inland, this is enhanced by the Atlantic (Irish sea) facing the coast. Concerning the precipitation RCP scenarios (Fig. 9**k and l**), there is a projected increase in precipitation between 10 and 30 mm with higher intensity along the coast.

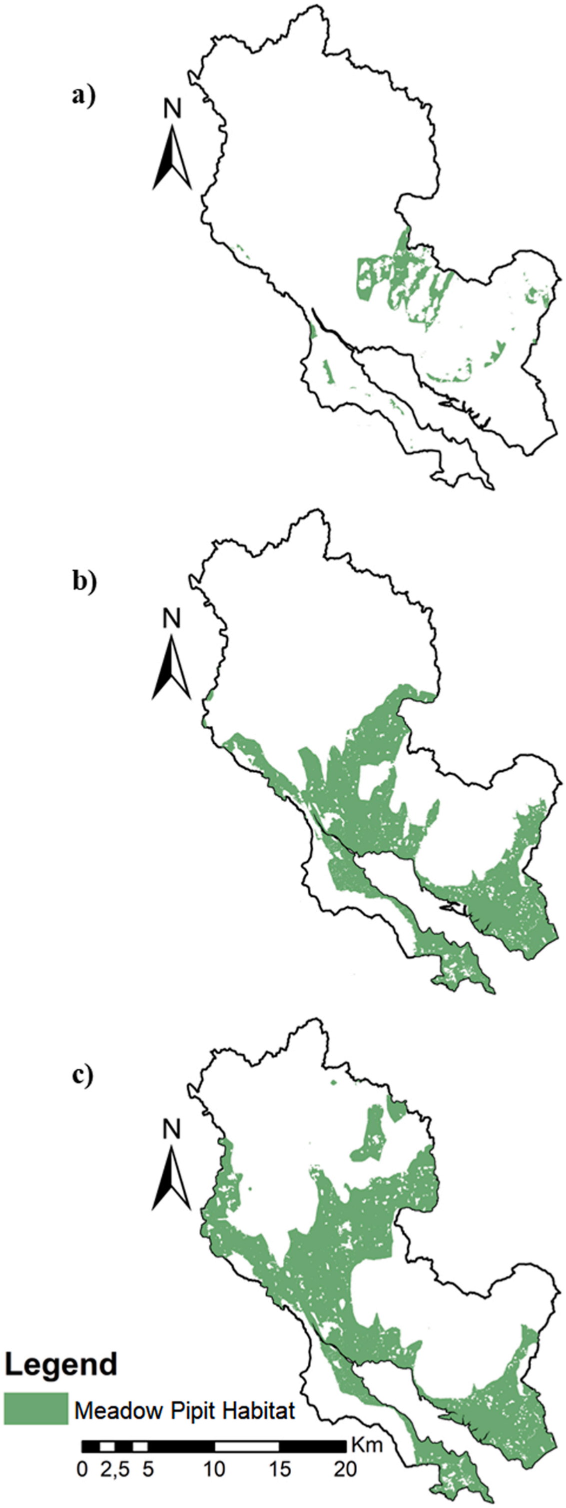

Fig. 10. Meadow Pipit habitat area distribution scenarios; **a)** current scenario; **b)** scenario RCP4.5; **c)** scenario RCP8.5.

3.4.2. Habitat mapping

Based on the data records for the Carlingford Lough catchment, the Meadow Pipit (*Anthus pratensis*) was the selected species to map the current and probable future habitat. It is classified as a near endangered species with decreasing current population in Europe based on provisional data (Lehikoinen and Virkkala, 2016) and is estimated to be decreasing at a rate of approximately 30 % in 11 years (Internafional, 2015). The main reasons for population decline are agricultural intensification (Del Hoyo et al., 2017) and weather severity and droughts which affect migration and potential winter range areas (O'Connor, 1999). This species thrives in wide habitat areas such as grasslands, coastal meadows, and, to some extent, artificial areas (Del Hoyo et al., 2017). Considering these pressures, the current habitat of the Meadow Pipit in the Carlingford Lough catchment and potentially favorable habitats for scenarios RCP4.5 and RCP8.5 were mapped (Fig. 10).

4. Discussion

4.1. Portuguese case study

The favorable habitat of the Iberian Frog represents an area of approximately 310 km^2 and is mainly located in the downstream part of the catchment forested waterbodies near the banks (Fig. 4**a**). As temperature rises, the habitat shifts upstream in the catchment to the same favorable temperature conditions with a decline of 25 % in the projected habitable area (233 km^2) for scenario RCP4.5 (Fig. 4**a**) and 79 % (66 km^2) for scenario RCP8.5 (Fig. 4**b)**. Since the temperature increase is significant, a decrease of favorable habitat area is projected for scenario RCP8.5. Thus, more conservation actions to preserve this endemic species should be implemented, namely improving habitat conservation and reinforce monitoring programs to mitigate the population decline. In this context, we can highlight the use of nature-based solutions, such as recovery/maintenance of riparian vegetation, and the afforestation with autochthones deciduous species (Terêncio et al., 2021).

4.2. French case study

The current habitat for the Black-tailed Godwit in the Couesnon catchment was mainly located near the coast next to the main river on wetland and grassland. The potential favorable habitat tends to shift inward along the river line (RCP4.5) and in the grassland up to 150 m altitudes where temperature conditions become favorable (Kleijn et al., 2010). For the current scenario, an area of 26 km^2 was observed (Fig. 6**a**) and an increase of probable habitat area was estimated to be 66 km^2 and 124 km^2 for RCP4.5 (Fig. 6**b**) and RCP8.5 (Fig. 6**c**), respectively. Although it seems that this species can prosper in the region with a potential increase of habitat area, it is noteworthy to state that the Black-tailed Godwit is a migratory species, but usually resides near the coastline in France (non-breeding conditions) (Lopes et al., 2013). The conditions projected for the future scenarios denote an extant habitat for passage only, which means that there is a risk of the Black-tailed Godwit stopping residing near the coast of the Couesnon catchment. Conservation actions should take place particularly in the management of breeding habitats such as have been applied in some Western European countries (Roodbergen et al., 2012). They should lead to the improvement of survival, breeding, and migration of this species (Gill et al., 2007), increase the coverage of agri-environmental schemes (Kleijn et al., 2010) and ensure the conservation and monitoring of migratory staging areas (Estrella and Masero, 2010).

4.3. Spanish case study

The favorable habitat for the thrive of the Spanish Fir in the catchment shifts longitudinally downward with the RCP scenarios considered. For the current scenario, an area of 330 km^2 is observed (Fig. 8**a**) and a decrease of probable habitat area was estimated, 171 km^2 and 169 km^2 for RCP4.5 (Fig. 8**b**) and RCP8.5 (Fig. 8**c**), respectively. Not only does the probable habitat area decreases but also shifts to a higher elevation where it usually thrives (Terrab et al., 2007). Conservation actions should therefore take place, mainly in natural system modification to prevent and reduce the risk of fire frequency and intensity, and pest control during severe droughts (Esteban et al., 2010).

4.4. Northern Ireland/Republic of Ireland case study

The current favorable habitat based on temperature ranges from the record database represents an area of approximately 20 km^2 and it is mainly located in the eastern part of the catchment (Fig. 10**a**). As temperature rises the potential habitat area increases, mainly located near the coast with the same temperature conditions as the observed records, with a projected area of 130 km^2 and 170 km^2 for scenario RCP4.5 (Fig. 10**b**) and RCP8.5 (Fig. 10**c**), respectively. Since the upstream of the catchment is composed mainly of meadows, and temperature becomes favorable in the upstream of the catchment, the potential habitat areas are prone to increase for both RCP scenarios. Although this species is expected to thrive, some conservation actions should benefit the success of their survivability such as alternative land management practices for meadows conservation, namely the promotion of low-intensity farming methods (Chiron et al., 2010; Peach et al., 2011).

4.5. Synthesis across case studies

There is a general projected increase of temperature as we move upstream in all case studies more pronounced in the main watercourse, but strongly dependent on the topography, rather than latitude. Though, the projected increase of temperature is higher in southern catchments (Portugal and Spain) when compared to northern catchments (France and Northern Ireland). Further, floods and droughts also play a role in ecosystem degradation (Talbot et al., 2018), nevertheless, the assessment of climate extremes of the climate datasets developed was not the aim of this study. Regarding the biodiversity outputs, it is worth mentioning that these results are constrained by the samples recorded at GBIF, which can lead to misinterpretation of the results. For instance, the Northern Ireland / United Kingdom case study showed very few sample points to assess spatial biodiversity in the catchment area. Also, while the surveys conducted may lack the presence of certain species does not mean that they are not present, or the location is unsuitable for them to thrive or serve as their habitat. The natural habitat conditions are also subject to other factors such as, anthropogenic pressures and invasive species, which can considerably lead to species mortality and ecosystem degradation, significantly declining the increase of these species' population. Thus, the distribution mapping of a certain species may depend on their adaptive capacity to survive in new harsher areas. It is therefore important to continue to collect field information and properly validate the data to improve habitat assessment to better characterize a species behavior.

One of the key factors determining species range is land cover, which when combined with climate change interaction, refine these predictions. The shift in range area of each species is based on each species-specific suitable habitat (land cover maps developed) and the suitable temperature range. Thus, the species-area range follows the temperature shift within the catchment, showing the highest decline in the Portuguese case for scenario RCP8.5 due to a higher projected temperature increase (up to 4 C). While for the other case studies, the temperature increase was not so noticeable (up to 1.7 C).

The increase of connectivity, as an adaptation measure, can be an important step in improving habitat conditions for every species (Da Fonseca et al., 2005; Hannah and Lovejoy, 2005; Opdam and Wascher, 2004). Nonetheless, it is of easier application for animal species than for plants (e.g. Spanish Fir) or forest ecosystems, where the development time can be very long (Vos et al., 2008). The conservation measures applied to the four vulnerable species considered could provide a protective umbrella to several other species helping to design priority areas for conservation and guide habitat restoration. River stream processes and functions are highly dependent on human landscape development (Jungwirth et al., 2002) and intensive use and changes of riverine landscapes will also affect ecological integrity. Thus, landscape planning and landscape ecology may help link socio-economic and ecological integrators to promote guidelines for watershed management and restoration (Torgersen et al., 2022). This may provide inventive ways for processing information to conserve and restore riverine ecosystems (Belletti et al., 2020). The combined effects of aquatic and terrestrial networks can contribute to a more accurate selection of priority areas for conservation and protection (Beger et al., 2010; Erős et al., 2011; Olson and Burnett, 2009).

5. Conclusions

The persistent and growing impacts of climate and land-use changes are a threat to ecosystems and biodiversity worldwide. These impacts will continue to affect the individual populations and species through changes in their habitat and behavior. By developing high-resolution climate datasets for both historical (1950–2018) and future periods (2041–2070), it is possible to assess the habitat of species at a regional scale with a less degree of uncertainty. Despite a certain limitation in using the GBIF database, this paper presents an integrated assessment of how species respond to climate change and habitat loss. This assessment can support the identification of proper actions for biodiversity conservation and provide guidelines to landscape planning and for the adaption to future management challenges. Not all the impacts in habitat changes can be negative, but even positive changes can require costly societal adjustments (Weiskopf et al., 2020). Landscape managers need proactive, flexible adaptation strategies that consider historical and future scenarios to minimize costs over the long term. Consequently, drawing strategies that focus on areas more susceptible to climate change that affect species' future habitat, through nature-based solution approaches, is one way to preserve vulnerable species. Therefore, accurately predicting responses of biodiversity trends to landscape changes is crucial for the sustainable management of any given territory. As a major novelty, our approach allows predicting key biodiversity responses from landscape attributes, through an improved integration of structural and functional changes related to the local land uses under realistic regional scenarios. Furthermore, another main challenge when developing methods for predicting landscape changes is the versatility to which those methods can be applied in other areas, contexts and scenarios. In this perspective, although our work encompasses four European catchments, it can easily be extrapolated to other landscapes with different anthropogenic pressure gradients, anticipating the regional consequences land use changes on biodiversity patterns, where the obtained algorithms are changeable to the universe of application (landscapes, ecosystems, communities and metrics) and future alternative scenarios intended. Framing our results at a catchment scale, the next steps will focus on the natural accounting framework (services and benefits) considering several management scenarios identifying the opportunities for the development of innovative incentive-based programs to conserve nature. Healthy ecosystems will be more resilient to climate change and so more able to maintain the supply of ecosystem services and biodiversity, highly linked to human health (Rapport et al., 1998; Sandifer et al., 2015). Therefore, biodiversity protection can help in the adaption to climate change. The new green European policies can lead to a strategy to reconnect natural areas using nature-based solutions to restore the health of ecosystems and allow species to thrive across their entire natural habitat.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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