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Changes in the waterbirds migratory patterns and wintering areas in Europe in relation to climate change

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Contents

Abstract 1
Introduction 3
  The migration of ducks and waterfowl 3
  Factors influencing timing and patterns of waterfowl migratory movements 3
  Wetlands 5
  Ecosystem services provided by migratory birds 6
  Climate change threats 7
    Important bird areas and the climate change 8
  Trying to predict the future: climate models and the SSP585 12
Materials and methods 15
  Databases description 15
    Climate data, geomorphological and environmental variables 15
    Species dataset 16
  MAXENT: model description and applicability 17
  Workflow 17
    Maxent model run 19
  Species in the study 20
Results 29
  Anas acuta (Northern Pintail) 29
    Present vs. forecasted summer 29
    Present and forecasted winter 31
  Anas crecca (Green-winged Teal) 34
    Present and forecasted summer 34
    Present and forecasted winter 36
  Anas platyrhynchos (Mallard) 38
    Present and forecasted summer 38
    Present and forecasted winter 39
  Aythya ferina (Common pochard) 42
    Present and forecasted summer 42
    Present and forecasted winter 43
  Aythya fuligula (Tufted duck) 46
    Present and forecasted summer 46

    - Present and forecasted winter 48
  - *Mareca penelope* (Eurasian Wigeon) 50
    - Present and forecasted summer 50
    - Present and forecasted winter 52
  - *Mareca strepera* (Gadwall) 54
    - Present and forecasted summer 54
    - Present and forecasted winter 56
  - *Spatula clypeata* (Northern shoveler) 59
    - Present and forecasted summer 59
    - Present and forecasted winter 60
  - *Spatula querquedula* (Garganey) 63
    - Present and forecasted summer 63
    - Present and forecasted winter 64
- Discussion 67
- Conclusion 74
- Bibliography 75

- Annex I 80
  - Models technical evaluation 80
    - Model for *Anas acuta* 80
    - Model for *Anas crecca* 82
    - Model for *Anas platyrhynchos* 85
    - Model for *Aythya ferina* 87
    - Model for *Aythya fuligula* 90
    - Model for *Mareca Penelope* 93
    - Model for *Mareca strepera* 95
    - Model for *Spatula clypeata* 98
    - Model for *Spatula querquedula* 100

Abstract

EN

Among the challenges that climate change poses for the near future, the possible effects on biodiversity and species distribution are among the riskiest. At the same time, these effects are also among the most difficult to predict, especially when considering migratory animals. The main objective of this thesis was estimate if and how the migratory routes of nine aquatic wintering anatids may be modified in response to climate change. All the analysed species are following the Black Sea - Mediterranean Flyway, during their migratory movements, in the central-Mediterranean region. Considering the environmental conditions of the recent past, this research highlights the interaction between the characteristics of the considered migratory species and the environmental variables that define their suitability conditions. Subsequently, these interactions are reconsidered given the predicted conditions of future climate scenarios, both in the medium and long term, identifying with the *Maximum Entropy* approach the possible changes in the areas suitable for the presence of anatids. Final results are discussed considering the consequences for the conservation of biodiversity.

IT

Tra le sfide che il cambiamento climatico pone per il prossimo futuro, i possibili effetti sulla biodiversità e la distribuzione delle specie sono tra le più rischiose. Al contempo, questi effetti sono anche tra i più difficili da prevedere, specialmente quando si considerano animali migratori. Questo lavoro di tesi ha come obiettivo principale quello di stimare se e come le rotte migratorie di nove specie di anatidi acquatici svernanti nella regione centro-mediterranea, che seguono la Black Sea – Mediterranean Flyway durante i loro movimenti migratori, possano essere modificate in risposta al cambiamento climatico. Considerando le condizioni ambientali del passato recente, la ricerca evidenzia l’interazione tra le caratteristiche delle specie migratrici considerate e le variabili ambientali che definiscono le loro condizioni di suitability. Successivamente, queste interazioni vengono riconsiderate alla luce degli scenari climatici futuri, sia a medio che lungo termine, identificando con l’approccio *Maximum Entropy* i possibili cambiamenti nelle aree idonee alla presenza di anatidi. I risultati sono discussi tenendo conto delle conseguenze in ambito di conservazione della biodiversità.

Introduction

The migration of ducks and waterfowl

Ducks and waterfowl, bird species which belong to the genus *Anas,* are a range of migratory species that breed at boreal and Arctic habitats latitudes, and winter along the shores of large water bodies. Since their nonbreeding ranges widely overlap and different species assemble into the same flocks throughout migratory and winter seasons, different ducks and waterfowl species have developed to exploit slightly different habitats and resources within shared territories. Such differences might lead to interspecific variation regarding both key habitat patches and network pathways (Lamb et al. 2019).

In the Northern Hemisphere, a generalised migratory route can be evidenced as a periodic, collective movement occurring from North to South during autumn season, followed by a permanence until the end of winter season. In spring it occurs a reverse from South to North, where waterfowl spend the breeding months until the next migration cycle starts. Thus, during the breeding season, many ducks occupy nesting habitats in areas of subpolar vegetation even beyond the northern borders of boreal latitudes, and the timing of the migration is usually synchronized. However, individual species may differ considerably in their use of breeding areas. According to Lamb et al. 2020, *Anas* species generally prefer to nest in relatively flat areas near large lakes or coastal areas. Moreover, they suggest that waterfowl choose areas with lower annual precipitation and where ranges of annual temperatures are lower. These mild climate conditions might possibly improve different factors affecting *Anas* species fitness; for example, nest cover and foraging opportunities on invertebrate prey during the breeding season could increase. In addition, the energy costs of incubation, the threats of nest destruction and duckling loss from exposure to cold and excessive wet conditions could be reduced (Ballard et al. 2021).

As far as it concerns the non-breeding period, important geophysical features of aquatic habitat across *Anas* species include shallow water depths and proximity to the coast. According to Smith et al. (2019), these outputs are consistent with previous studies in which it was observed, through aerial survey data, that non-breeding ducks were clearly confined to nearshore waters. Moreover, according to the literature, both niche specialisation and habitat partitioning are shown to be higher during post-breeding migration and moult rather than during pre-breeding migration. For instance, Lamb et al. (2020) suggest a difference in habitat selection and partitioning between the two migratory periods, pre- and post-breeding; during post-breeding and moult it is crucial the access to habitats with abundant resources. This limitation restricts the range of suitable habitats available. On the other hand, pre-breeding roosting areas are used for shorter periods and they do not include a no-flying time period.

Factors influencing timing and patterns of waterfowl migratory movements

Throughout the course of migration, birds respond to several stimuli that triggers the migratory cycle. Instinctive reactions play a crucial role in guiding migratory behaviour, alongside decision-making processes: indeed, birds often rely on innate instincts to navigate their migration routes and determine when it's time to depart toward a specific direction or arrive at specific destinations. On the other hand, they sense environmental cues and make many important decisions based on them, including small-scale choices about where to go, how long to remain, and when to leave. Each of these decisions affects the others and it is ultimately a contributor an individual’s fitness (O’Neal et al. 2018).

Migratory ducks can cover wide distances in a relatively short period of time and exploit the seasonal food availability at the high Arctic latitudes during summer months, while avoiding scarcity during the severe Arctic winter by returning to temperate or tropical areas (Somveille et al. 2015). Bird migration is therefore predictable, as migrants tend to synchronise their spatial distribution with the seasonal availability of food resources (Xu et al. 2019).

The amount of time during which migrating birds spend at stopover sites, or stopover duration, partially determines an individual's access to resources, the environmental conditions encountered, and the exposure to both natural predation and hunting by humans, which in turn affect survival and fecundity. As such, migratory behaviours such as stopover duration can have a considerable effect on populations of migrants and plans for their conservation (O’Neal et al. 2012). The decision of when to migrate is particularly important since it requires giving up existing conditions, enduring conditions at altitude, and taking risks related to conditions of an unknown destination. Given that the timing of spring departures has a direct effect on reproductive performance, many bird species have evolved endogenous mechanisms in regulating the migration timing to breeding grounds. However, during autumn, birds seem to depend more on external factors as, for example, food availability, risk of predation, social context, and weather conditions (O’Neal et al. 2018).

In the context of the phenomenon of bird migration, understanding the migratory dynamics of waterfowl is of particular importance due to their important role in linking diverse and distant ecosystems, their dual status as popular birdwatching targets and gamebirds, and their role in the propagation of zoonotic diseases (Weller et al. 2022). All these characteristics asked for the implementation of population and habitat management programs.

Among the environmental factors that most influence the timing of migration, weather has been highlighted as a key factor for the majority of avian taxa, but its specific role in regulating fall migration remains uncertain (Notaro and Schummer 2016). There are some different reasons for the limited understanding of how weather conditions can affect duck migration; in particular, one among all is that the timing of these species departure is particularly complicated. While passerines often operate according to a time-minimization strategy (Dänhardt and Lindström 2001), ducks in autumn migration typically remain in mid-migration stopovers for a few days, even if there appear to be weather conditions suitable for migration. In addition, the timing of migration is further complicated by hunting pressure and the quality of non-breeding habitats (Hagy et al. 2014).

A recent study has demonstrated a mechanistic connection among the degree of wind assistance perceived by waterfowl, their basal corticosterone levels and associated departure probabilities (Eikenaar et al. 2017). It has been reported that migratory birds (including ducks’ species) are able to distinguish between favourable and negative wind conditions rather than classifying wind on a continuous scale of favourability.

Precipitation is another factor that has the potential to regulate the migration probability of waterfowls due to its flight obstruction, influence on thermoregulation, and mortality potential. The probability of departure may also be affected by weather conditions that influence the mechanisms of orientation. For example, stars are supposed to assist the orientation of ducks and other waterfowl during flight, so the presence of clouds obscuring the hight sky may reduce the departure probability (O’Neal et al. 2018).

Another relevant factor influencing the energy balance of *Anas* species, the progression of their migration, and the latitudinal distribution of migrants over the season is air temperature. In addition, the temperature difference from the previous day is another potential driver for duck departures. Some migrators may have an environmental temperature at which they no longer feel comfortable staying in a stopover. For this reason, the minimum temperature of a single day can influence the probability of departure. Finally, barometric pressure and pressure variation can also serve as drivers to future conditions at current and future locations of migratory waterbirds (Notaro and Schummer 2016).

In addition to meteorological factors, habitat factors have also been shown to influence duck migration. Ballard et al. (2021) compared wetland types, including cultivated, seasonal, semi-permanent wetlands, and lakes. Per unit area, the highest used by duck species occurred to be semi-permanent wetlands, followed by seasonal, farmed wetlands, and, at last, lakes. Several factors influenced duck use on local and landscape scale, such as the area of the wetland, the abundance of vegetation, and the number of wetlands in the surrounding landscape. It has been observed that, considering the semi-permanent wetlands habitat, local factors within wetlands were more important in determining the presence of duck than landscape factors.

According to Lamb et al. (2020), a previous work on several species of eiders has shown that sea ice plays a significant role in determining pre-breeding migration patterns, habitat use at stopovers sites, and prey availability and composition onward the whole migratory route. Among waterfowl in the northern hemisphere, the decision to undertake southward migration is believed to depend mainly on energy budget considerations. As food availability decreases in autumn and winter conditions, metabolic costs increase, and food becomes more difficult to acquire. This trend persists until staying at high latitudes is more energetically expensive than expending energy to move south. The effect of falling temperatures and the presence of snow and ice are the main indications of ducks and geese migration, for both the short term and over longer periods, as cumulative measures (Weller et al. 2022).

Wetlands

Wetlands are the primary stopover and feeding sites for waterfowl and, for this reason, have been the subject of management and research in many different landscapes in Europe, Asia, and Africa. These ecosystems have the common role of facilitating the transition of duck species from wintering areas in central Africa and European southern latitudes to breeding areas in Siberia and the northern European continent. These landscapes differ in their dispersal across the landscape, the nature of the wetlands used by waterfowl, behaviour of ducks, and wetland ownership and management (Ballard et al. 2021).

Millions of wetlands (lakes, ponds, rivers, swamps) characterise the boreal habitat, comprising over 80 % of the world's freshwaters (Guillemain et al. 2013). Their importance for breeding ducks is likely to increase in some regions, given the fact that changes in adjacent biomes make them less hospitable. For example, as the prairies in North America become drier, the most suitable areas for duck will be found in the eastern and northern territories of this biome and, eventually, in boreal areas (Holopainen et al. 2015). In Southern Europe, climate change is also expected to reduce the availability and quality of wetland for ducks due to drought conditions (Guillemain et al. 2013). As an additional cause, the boreal biome itself is changing as well; modern forestry is leading to changes in both water dynamics and chemistry, while global climate change threatens to reduce the boreal biome geographical extent. These changes are likely to affect the diversity of wetland, as well as their food resources, plant species and predators, which in turn affect the quality of habitat for breeding ducks (Li et al., 2018).

Wetlands are among the worldwide most threatened habitats: about half of all wetlands that existed in the last century have been lost due to agriculture, urban expansion, and management practices (Holopainen et al. 2015).

Wetland habitat suitability is described as the relationship between the habitat requirements of a species, that is the fundamental niche, and wetland habitat factors that influence the use of a site. Interpreting habitat suitability models, two main factors are compared: the realised niche and habitat selection. For the definition of the first one, the main role is played by the biotic interactions and the dispersal abilities of the species; as it concerns the habitat selection, it is inherently very sensitive to both temporal and spatial scale. Although the whole extent of wetland can determine waterbird diversity, the abundance of suitable habitat is more important for waterbirds, as not all wetland biotopes are suitable for the morphology or ecological habits of ducks (Xu et al. 2019).

Food availability, that is determined by forage production and inter-specific competition (depending on species density), is likely to influence the overall amount of time ducks spend at a stopover (O'Neal et al. 2018).

Ecosystem services provided by migratory birds

In all ecosystems, migratory birds act as key links in their ecological functions, within and among systems. Birds are extremely mobile and can respond rapidly to elevate or limited availability of resources, allowing them to be more efficient than other vertebrates in exploiting them. For this reason, they can link, in both spatial and temporal scales, ecosystem processes and flows separated by great distances and time (Donnelly et al., 2019).

Therefore, migratory birds have demonstrated to contribute substantially to the provision of ecosystem services, i.e. direct or indirect benefits to human well-being that arise from ecosystems components and functions (Gissi et al., 2015).

Waterfowls act as strong connectors among ecosystems, facilitating the movement of energy and materials across the ones interested and affected by waterfowl network structure (such as wetlands, rivers, coasts, forests, and marine ecosystems); at the same time, they contribute to modifying, at different scales, each of the systems by playing the makers role. On these functions strongly depend the sustainability and biodiversity of ecosystems, as well as the spread of species to other ecosystems them (Kohl et al. 2022).

Migratory waterfowls directly or indirectly participate in genetic transfer, as well as in the transfer of materials and energy; in particular, their key roles are related to food supply, plant and animal dispersal, and cultural interest. Among migratory species, some waterfowls are huntable in Europe and thus provide ecosystem services in the form of meat. In addition, as many other migratory birds, they are crucial indicator species for monitoring ecosystem health. Additionally, they can alter the composition of resident communities and change ecosystem functioning by transporting nutrients and organisms at local, regional, and global scales (Si et al. 2018). In *Table 1* are listed the ecosystem services provided by *Anas* species.

Table 1: Selected examples of ecosystem services provided by waterbirds (Green and Elmberg 2014).

Category	Ecosystem service
Provisioning	Meat
	Feathers for clothing and ornaments
	Grease for waterproofing
Supporting	Animal propagule dispersal
	Plant propagule dispersal
	Nutrient cycling
	Stimulating primary productivity
	Animal and plant diversity
	Bioindicators for animal and plants
	Bioindicators of nutrients/contaminants
Regulating	Pest control
	Disease surveillance
Cultural	Recreational hunting
	Birdwatching
	Ecotourism

Climate change threats

Traditionally birds have received substantial attention from the research, and this is why the consequences of climate change on their populations have already been deeply explored. However, for many reasons, studies are oriented towards specific groups of bird, in particular songbirds nesting in cavities. These species might be particularly affected by a changing climate because of their small size and high energy requirements compared to the size (Lamb et al. 2020).

On the other hand, a lot of waterfowl, and most ducks among them, depend on wetlands that are strongly threatened by changes in anthropic climate and land use. However, studies about the impact of climate change on waterfowl species are not as common as for other bird species. Among literature, phenological changes in waterfowl migration patterns have been linked to habitat conditions and weather patterns altered in both wintering and breeding areas (Weller et al. 2022).

Stopovers are essential sites along the migratory pathways, since waterfowl often are not able to travel between wintering and breeding grounds in one single flight. These wetland resting sites are patchily distributed, and often very distant among each other in an environment dominated by human presence. The total migration period is strongly dependent on the amount of time spent at stopovers, since it accounts for the greatest part of the total migration period, and it far exceeds the time spent in flight (Merken and Deboelpaep 2015).

It is defined as functional connectivity of migration networks the degree to which the configuration of the habitat helps waterfowl movements within and among breeding, non-breeding, and stopover sites. Functional connectivity creates a link between landscape features and species' dispersal traits and is crucial to study how spatial distribution of suitable habitats might influence populations of migratory species. (Si et al. 2018). Many waterfowl follow a network of stopover patches through their route travel between breeding and non-breeding grounds with the aim to rest or refuel before proceed toward further sites (Merken and Deboelpaep 2015).

It is settled that climate change is determining shifts in the geographic distribution of an extremely large range of organisms (Kikstra et al. 2022). Such changes may develop slowly, due to differential population trends at the two extremes of the geographic range, or in a more rapid way, through behavioural plasticity by individuals inside the population they are part of. Even if waterfowl, including duck species, have shown strong fidelity to their wintering grounds, they are part of those species for which changes, in both timing of movements over wide distances and geographic distribution, may occur extremely rapidly, and these are already being studied (Guillemain and Hearn 2017).

Therefore, the future possibly new distributions of ducks' populations may not overlap with the distribution of protected areas, which have been designated to conserve them, anymore in the coming years; hence a geographical misalignment may occur. To avoid this mismatch, it is needed the designation and management of new protected areas at the corresponding most crucial sites. These areas provide long-term habitat protection and also help population distribution shifts since waterfowl often prefer to establish in such protected areas their range expansion. From an ecological perspective, one problem, is to study and understand the habitat requirements of the species, in order to decide where to establish or enhance the network of such protected zones, all along migratory routes (Leimbach et al. 2023).

Finally, the synchrony between population distribution and resources availability also makes migratory ducks particularly vulnerable; changes in climate and land cover cause alterations in food and prey availability along the flyway. Thus, it is crucial to understand the ecology of waterfowl and their migration for the conservation of *Anas* species (Si et al. 2018).

Important bird areas and the climate change

That Mediterranean wetlands are strategical areas for biodiversity in the face of global change is well-established. However, these wetlands are experiencing severe degradation and biodiversity is being lost at extremely high rates due to increasing pressure from human activities such as pollution, drainage and agricultural intensification as well. Moreover, due to their critical ecological importance at global level and the large amount of ecosystem services that they provide (from both regional and local scales), conserving Mediterranean wetlands is crucial for the implementation of the post-2020 global biodiversity framework and the Sustainable Development Goals (Fraixedas and Galewski, 2019).

Since 2010, the Mediterranean Wetlands Observatory have assessed the status and trends of Mediterranean wetlands, and two regional Outlooks have been published: Mediterranean Wetlands Outlooks 1 (MWO1) and Mediterranean Wetlands Outlooks 2 (MWO2), characterising wetlands as one of the very few ecosystems that have been determined at this scale (Perennou et al., 2020).

The Venice Lagoon

The Lagoon of Venice is the largest coastal lagoon in the Mediterranean; it covers an area of 55.000 ha along the Adriatic Sea. Most of the lagoon consists of an open water body about 37.000 ha in size, 5.000 ha of this wide area are tidal flats less than 0.5 m deep which are regularly exposed during low tides. About the remaining area, 26.000 ha are shallow bottoms (0.5–1 m deep) and 6.000 ha are characterised by deeper channels. Along the lagoon borders 9.000 ha are occupied by fish farms, that are completely surrounded by dykes and where influx of tides is regulated by the owners. Springtide excursion is about 1 m, among the highest values in the whole Mediterranean. Venice Lagoon presents temperate climate, and for its ornithological value, since it is one of the most important breeding sites in Italy and, furthermore, it is probably the most important wintering site for waterbird in the Mediterranean Sea, the whole lagoon was declared a Special Protection Area (IT 3250046 Laguna di Venezia) in 2007 according to the Birds Directive2009/147/EC (Scarton 2017).

After 1600 years from its foundation in 421 A.D., the sea level rise trend, which is triggered by human activities of current historical period, poses serious doubts on the survival of Venice and its lagoon (Kikstra et al. 2022).

In order to preserve the city from floods, have been adopted many short- and medium-term solutions, as for example, building a mobile gate system at the sea inlets (Mo.S.E.) or rising the pavement level. However, the predicted sea level increase in the upcoming decades, temporary closure of the inlets will become obsolete far before the end of this century.

In a few decades indeed, it would probably be a matter of deciding about when to open the mobile gates, more than about closing them (Mel et al. 2021). To prevent the city of Venice from a definitive submersion, it seems that cannot be avoided the permanent closure of the sea inlets. Consequences of the permanent closure of the lagoon will consist in deep modifications of its ecological structure and functioning, with a shift from the actual estuary condition into a coastal brackish lake or into a system of coastal lakes (Tagliapietra and Umgiesser 2023).

At present, tides drive the ecological dynamics of Venice Lagoon. Cyclical water movements shape both the landforms and the physical-chemical gradients that determine the biological community structure of this unique ecosystem (Mel et al. 2021). Closing the lagoon more and more permanently, tides' ecological function would be annihilated, and this may make the system much more fragile; indeed, tidal exchange renews the lagoon waters removing catabolites. In general, tides are the main driver for the maintenance and new formation of saltmarsh habitats, such unique in the Mediterranean area. Permanent sea inlets closure would, moreover, stop the exchange of genetic material with the sea too, not allowing the fluxes inside and outside the lagoon of marine organisms that see this wetland ecosystem as the ideal place to reproduce (Tagliapietra and Umgiesser 2023).

Camargue

The Camargue is a large system of wetlands in France that corresponds with the delta of the Rhône River, and it is one of the largest and most biodiverse Mediterranean wetlands (Fraixedas and Galewski, 2019).

In 1986 it was assigned to Ramsar sites community since its international importance for staging, wintering, and nesting waterfowl. During hottest months, from April to September, the amount of the evaporation exceeds precipitation; on the contrary, after September rainfall rate far exceeds the evaporation. Camargue coastline is characterised by a microtidal range of about 30 cm. It is frequently swept by strong winds, which not only drive coastal currents, but are the main factors that lead to a homogenization of salt concentrations within the lagoons, moreover, forcing water exchanges among them. The high amount of sand transported by coastal currents, contribute to enlarge the strand plain and modify coastal dunes location and conformation along the Rhône shoreline (Davranche et al., 2024).

Over the last decades, some major changes have occurred, from in land-cover, to land-use and water management. Over the last 50 years, Camargue has been characterised by rapid agricultural intensification (especially rice cultivation) and crop cultivation, including market gardening. Having a look to the solutions that are being applied to this area, the Camargue can be considered an excellent example of how a co-evolutionary dynamic of natural and cultural interactions can be carried on, and for this reason, it can be seen as a good case study of the state of biodiversity, applicable to other similar wetland habitats, along Mediterranean coasts (Fraixedas and Galewski, 2019).

It is also one of the major sites for waterfowl hunting in Europe, ducks being predominant in waterfowl, and, hence, the main targets for wetland management for private hunting (Vallecillo et al., 2023).

Ebro delta

The Ebro Delta is the second most important Spanish wetland after Doñana (Atlantic coast of Andalusia, Spain). Located on north-east Spainish coast, in the Western Mediterranean (Catalonia, Spain), this wetland has a significant environmental value because of the wide diversity of habitats that characterise it, like coastal lagoons, marshes, sea, river, dunes and beaches, freshwater ponds, swamps. It hosts a rich amount of biodiversity; for instance, more than a half of the species of migratory birds in Europe stop inside the Ebro delta for wintering, nesting and as a resting area, along their migratory flyways (Genua-Olmedo et al., 2016). This is the reason why it is the second most important 'Special Protection Area' for waterfowl in Spain. The Ebro Delta is recognised in a few national and international frameworks for environmental conservation: Natural Park (Spain, 1983); International Interest of Euro-African Wetlands, category A—urgent priority (UNESCO, 1962); wetland of international importance (Ramsar Convention, 1971); special protection area for birds ZEPA (European Union, 1979); Natura 2000 Network (European Union, 1992) (Rodríguez-Santalla & Navarro, 2021).

Lagoons of the Ebro Delta have been classified as coastal brackish/saline lagoons and they are defined "priority habitats" under the EU Habitats Directive, according to the Ramsar program. Nowadays, the lagoons communicate with the sea through very restricted channels, and they predominantly receive fresh water through drainage network that come from the river; Ebro River also collect the rich nutrient water coming from rice fields (Day et al., 2019).

Despite the Ebro Delta is screened by protection features, there are several hazards that threaten its littoral. First of all, the rising sea level, which is strictly associated with global warming, represents one of them, especially in the medium to long term; as it concerns other more immediate ones, a relevant risk is the lack of sediment inputs caused by the human regulation activities of the Ebro River (irrigation, dams, hydroelectric power generation and reservoirs). All of this is causing the erosion and retreat of some areas of its coastline. Finally, one more threat of the Ebro Delta is the environmental degradation of the coastal lagoons, predominantly caused by the increase of storms intensity and frequency (Day et al., 2019).

Turkey and its Straits

Turkey is located on the eastern migratory flyway of the Western Palaearctic, running longitudinally for Palaearctic-African migrants and latitudinally for Palaearctic-Indian migrants. Turkey is of great importance for large numbers of migrating and wintering waterbirds not only thanks to its coastal region, but also because of its inland lakes and marshes used by the migrating birds as feeding and resting places (Hambäck et al., 2023).

Given its strategic position, Turkey hosts relevant number of wetlands on both Mediterranean and Black Sea shorelines. Among all, two of the most important wetlands are Gediz Delta and Kızılırmak Delta.

Gediz Delta is situated on the coast of the Aegean Sea, in the Eastern Mediterranean basin. It is composed of a wide extended patch of freshwater and salt marshes (5000 ha), salt flats (3300 ha), and four lagoons. The Delta plays a crucial role in maintaining the biogeographic diversity in the region, and it is globally recognized as an internationally important stopover site for breeding and wintering waterbirds species (Arslan et al., 2021).

Being one of the 14 wetlands under the conservation programme of the Ramsar Convention in Turkey, the Kizilirmak Delta is located in the Black Sea Region. It covers a total area of 56,000 ha, half of which are included in the Ramsar area. Due to the fact it incorporates several different habitats (Black Sea, lakes and rivers, meadows, reeds, swamps, sand dunes, pastureland, forest, and fertile agricultural soil), the Kizilirmak Delta is characterized by its rare, unique biological diversity (Ozturk et al., 2015).

Finally, two strategic transitioning wetlands correspond to the straits dividing Europe from Turkey. Dardanelles and Bosphorus Strait, which are among the most important migration routes in the Western Palaearctic region, are located in the Northeastern part of the Mediterranean basin. Breeding waterbirds populations in Europe migrate further south to wintering areas in Middle East, Arabic Peninsula, until Pakistan and India (Hambäck et al., 2023).

East Mediterranean coast

The Hula Valley is located in Israel, and it originally was a 6,000-ha wetland, made of a large freshwater lake and several swamps. It is situated in the northern part of the Jordan Valley, as part of the watershed basin of the Sea of Galilee. It was drained in the 1950s, with the aim to increase the water availability for the country and to convert into arable land the swamps. In more recent years, 100 ha of the new cropland were re-flooded, allowing the formation of the Agamon Lake, and a network of almost 90 km of drainage canals and shallow flood. The Agamon project helped rehabilitate the diverse wetland ecology including an important resting habitat for migrating birds en route between Africa and Europe (Cohen-Shacham et al., 2015).

Wetland in Sudan

South Sudan has an area of around 640,000 km^2. This country is located in the Nile catchment area, and it receives water from the highlands of Democratic Republic of Congo, Central African Republic, Ethiopia and Uganda. The lowest part of the Nile basin forms several wetland ecosystems, such as Sudd wetland, Machar Marshes wetland and other smaller ones (Mulatu et al., 2022).

The Machar Marshes wetland is one of the largest wetlands in Baro-Akobo-Sobat (BAS) sub-basin and it comprehends about 13.2% of the basin. This wetland is a habitat for almost 400 different bird species and more than 100 mammals. Due to its climatological and environmental characteristics, it is one of the most relevant wintering sites for a lot of migratory bird species, including duck and waterfowl, for the Sub-Saharan region (Mulatu et al., 2022).

The Sudd wetland is situated in the central part of South Sudan. It is one of the world’s largest wetlands, covering a surface of 57,000 km^2, reaching an area of up to 130,000 km^2 depending on the discharge from the Albert Nile. It was designated by the Ramsar Convention as a wetland of International Importance in 2006. Swamps usually near to the course of the main river are permanently wet. However, a relevant percentage of the wetland is characterised by seasonal swamps, which depend onto flooding of Nile River, or onto the amount of rainwater during the wet season, when ponds are seasonally filled. The Sudd is also crucial in regulating climatological patterns in the Horn of Africa, the Sahel, and the East Africa region in general. Sudd wetland acts as a barrier against the enlargement southward of the Sahara Desert and this is the reason why preservation and management of this such pivotal wetland is expected to be the most significant contribution for the country, and the surrounding regions, against the impacts of climate change (Desai, 2020).

North Africa wetlands

Along the north African coasts there are several, very strategic stopover and wintering sites for waterbird populations since it is placed along the migratory flyways (in particular Palearctic–African migration) of a lot of Palearctic and sub-Saharan species. North Africa wetlands are therefore pivotal foraging sites since migratory and wintering species need to build up sufficient fat reserves, which are essential for their survival and breeding at high latitudes nesting grounds (Boumaaza and Houhamdi, 2017).

Among North Africa countries, Egypt is located on a strategical position along the main migration routes connecting Europe and Middle East with African continent. The lakes in the North of Egypt, which include Burullus, Manzala, Bardawil, Idku and Maryout, are critical strategic stopovers for thousands of migratory birds, and wintering sites for breeding species. Migratory waterbirds rest at these lakes each year, especially during autumn and spring, to refuel before reaching the destination of their journey to the Sahara or back to breeding grounds, across the Mediterranean Sea. Northern lakes are not only important stopover sites, these wetlands are indeed places for wintering months for many waterfowl species too (Keshta et al., 2022).

Migration between Europe and Africa occurs along three main migratory axes: the East Atlantic, the Central Europe-Black Sea-Mediterranean and the West Asian flyways; Tunisia and Algeria wetlands are strategic stopover sites for waterfowl migrating along the Central Europe-Black Sea-Mediterranean. Ducks migrating from breeding sites of north and central Europe pass over Greece and Italy, reaching African coasts after they have flown over Mediterranean Sea (Elafri et al., 2017).

The region near the Algerian Tunisian border, includes one of the most important wetland complexes of North Africa (Tonga Lake, a shallow freshwater marsh of 2,700 ha) and it is populated by a large number of wintering or resident waterbird species. Since North African wetlands are under strong anthropogenic pressure, it is a priority the identification of Important Bird Areas (IBAs) in the region, in order to ensure and plan conservation and management actions (Djelailia et al., 2018).

Trying to predict the future: climate models and the SSP585

Emissions scenarios form a key tool in the scenario-based literature, informing the Intergovernmental Panel on Climate Change's (IPCC) assessments (Kikstra et al. 2022). The history of IPCC assessment reports nowadays covers many emissions scenarios generations. These include the "1990 IPCC First Scientific Assessment" (SA90), the "1992 IPCC Scenarios" (IS92), and the 2000 "Special Report on Emissions Scenarios" (SRES). They also include more recent emissions scenarios developed outside the IPCC, in particular the "Representative Concentration Pathways" (RCPs) and the "Shared Socioeconomic Pathways" (SSPs) (Riahi et al. 2017).

These emission scenarios aim to explore possible trajectories regarding the possible evolution of global climatological and environmental dynamics, in relation to different predicted CO2 emission scenarios. They include those trajectories that are consistent with current expectations, as well as more uncertain developments that show trajectories that would meet specific goals or explore possible high impact futures. They are not predictions – as the future is fundamentally uncertain. This uncertainty is the key reason to explore multiple scenarios (Strandsbjerg et al. 2021).

A new set of scenarios has been developed for Scenario MIP, which is the part of the international Coupled Model Intercomparison Project 6 (CMIP6) of the World Climate Research Programme (WCRP), compraising scenario runs for the 21st century. These new scenarios show different socio-economic developments and different pathways for the atmospheric concentrations of greenhouse gases (Kikstra et al. 2022).

It is used a predefined subset of these scenarios, all over the world climate research institutes have performed climate change simulations for the CMIP6. At first, the obtained results provide a basis for the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR6). There were designed five narratives which describe different development paths of society and form the basis of the SSP scenarios (from SSP1 until SSP5); in this work the focus is set for SSP5, which considers a full fossil-fuelled development (Pirani et al. 2024). While global markets are increasingly integrated, determining a constant technological progress and new daily innovations proposals, social and economic development is still based on an increased exploitation of fossil fuel resources, with a predominant percentage of coal (Welch Ivo, 2024). Even if economy is growing at global level, local environmental problems, for instance air pollution, are not being tackled successfully. With the aim to structure the variety of possible scenarios, it was determined the intensity of the additional radiative forcing or rather the degree of climate change (based onto the greenhouse gas effect produced by anthropogenic sources). The classes of climate effects (radiative forcings) employed correspond with a good approximation to RCP scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). From the combination of the five pathways with the different climate forcings it is obtained a scenario matrix (Fig. 1) (Pirani et al. 2024).

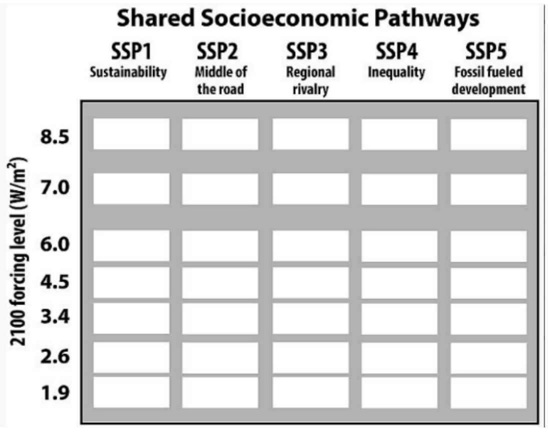


Figure 1: scenario matrix (Pirani et al., 2024).

For Scenario MIP, it was reached a global agreement on four combinations inside the matrix as standard scenarios. The four outputs, which are shown in *Figure 2*, were simulated in the scenario runs funded by the Federal Ministry of Education and Research (BMBF), with the aim to project CMIP6, over a time period up to the year 2100 (Pirani et al. 2024).

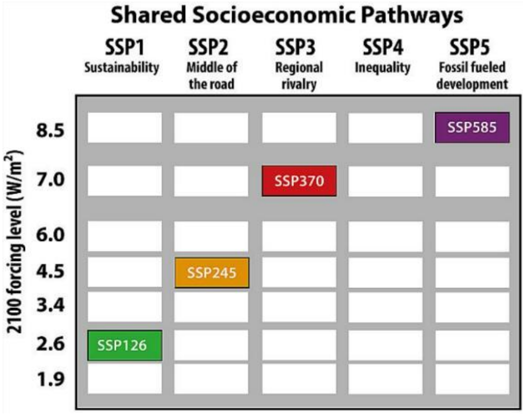


Figure 2: ssps within the scenario matrix (Pirani et al., 2024).

Individual scenarios denomination comprises, for the first part, the name of the basic pathway, which is secondly followed by two numerals which indicate the additional radiative forcing reached by the year 2100, in tenths of watts unit.

The scenario chosen for this thesis is the SSP585: it predicts an additional radiative forcing of 8.5 W/m² by the end of the 21st century and it represents the worst scenarios among the ones described in the literature. SSP585 scenario is therefore an update of the CMIP5 scenario RCP8.5, combined with socioeconomic features. In *Figure 3* are shown the predicted trend according to different CO2 emission and concentration pathways (Pirani et al. 2024).

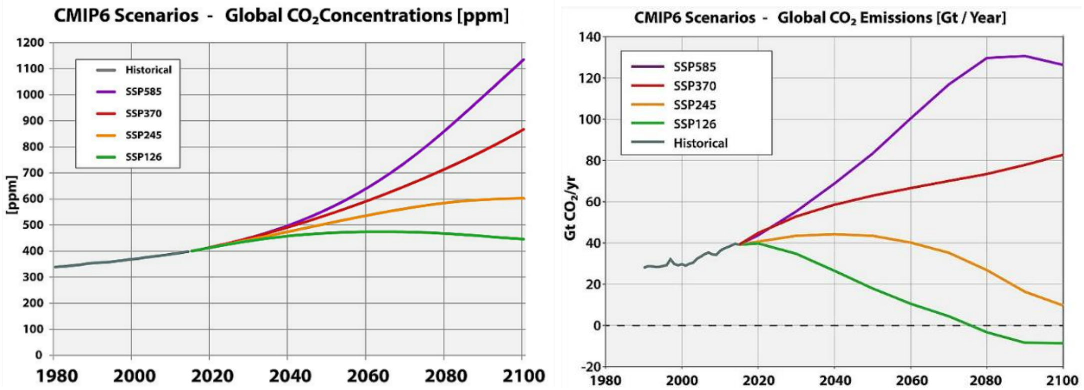


Figure 3: global CO2 emission scenario and global CO2 concentration scenario (Pirani et al., 2024).

The main objective of this thesis will be to estimate if and how the migratory routes of nine aquatic wintering anatids may be modified in response to climate change. All the species analysed are following the Black Sea - Mediterranean Flyway, during their migratory movements, in the central-Mediterranean region. Considering the environmental conditions of the recent past as a proxy of the present climatic baseline, this research highlights the interaction between the characteristics of the considered migratory species and the environmental variables that define their suitability conditions.

Materials and methods

Databases description

Climate data, geomorphological and environmental variables

CMIP

The Coupled Model Intercomparison Project (CMIP, https://wcrp-cmip.org/cmip-phase-6-cmip6/) is an international project on climate modelling. It has been designed to better understand changes in the climate, for both recent past and closer to farther future. CMIP has been planned in different phases, each with a new improved climate model experiment protocol and data distribution mechanisms. CMIP6 is the most recent phase, whilst the future next phase, CMIP7, is still in the organisational stages.

Worldclim

Worldclim is a respository of global weather and climate data and it can be used for spatial modelling and mapping (https://worldclim.org/data/cmip6/cmip6climate.html). The whole amount of data is available for free for academic scope and non-commercial use as well. Weather and climate data are available divided in gridded features, for both historical and future situations, at mid or high resolution formats.

Historical data comprehend years between 1970 and 2000, and this is why they are data about recent past, not so far in historical periods. Data are monthly classified and there are climate data for minimum, mean, and maximum temperature, solar radiation, precipitation, water vapour pressure, wind speed, and for total precipitation. Moreover, there are 19 “bioclimatic” variables.

Data about future conditions are available at CMIP6 downscaled future climate projections. Calibration (bias correction) and downscaling was performed with the current version of WorldClim. Monthly values of precipitation, minimum and maximum temperature were processed for four Shared Socio-economic Pathways (SSPs): 126, 245, 370 and 585 from IPCC scenarios and for 23 global climate models (GCMs). The monthly values are averages covering 20-years-periods (2021-2040, 241-2060, 2061-2080, 2081-2100). Finally, four spatial resolutions are available and are expressed as minutes of a degree of longitude and latitude: 10 minutes, 5 minutes, 2.5 minutes, and 30 seconds.

In this study we considered future climate projections according to the MIROC6 model associated with the SSP 585 scenario, with spatial resolution of 30 seconds. Among the climatic variables available maximum temperature and bioclimatic variables are taken into account.

As it concerns for the bioclimatic variables (https://worldclim.org/data/bioclim.html), they are derived from rainfall values and monthly temperature with the aim to generate more meaningful variables under a biological view point. Bioclimatic variables represent seasonality (for example, annual range in temperature and precipitation) annual trends (such as mean annual temperature, annual precipitation) and extreme or limiting environmental factors (for instance, precipitation of the wet and dry quarters, and temperature of the coldest and warmest month). A quarter is a three-months-period (1/4 of the year).

It has been decided to split the whole year into two seasons, called “summer” and “winter”. Months from April to September are considered “summer” season, while from October to March it’s “winter” seasonality.

Since each season is characterised by different temperature and precipitation parameters, different bioclimatic variables have been selected for “summer” and “winter” seasonality; after some tests run with Maxent it has been observed that “summer” was better defined by the variables mean diurnal range (BIO2), minimum temperature of the coldest month (BIO6), temperature annual range (BIO7), mean temperature of the coldest quarter (BIO9), mean temperature of the coldest quarter (BIO11), precipitation of wettest quarter

(BIO16), and precipitation of driest quarter (BIO17). Instead, "winter" was better described by mean diurnal range (BIO2), maximum temperature of warmest period (BIO5), temperature annual range (BIO7), mean temperature of driest quarter (BIO9), mean temperature of warmest quarter (BIO10), precipitation of wettest quarter (BIO16), and precipitation of driest quarter (BIO17) (Legend of the codes in Table 2).

Table 2: worldclim bioclimatic variables (from https://worldclim.org/data/bioclim.html)

BIO 1	Annual Mean Temperature
BIO 2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO 3	Isothermality (BIO2/BIO7) (×100)
BIO 4	Temperature Seasonality (standard deviation ×100)
BIO 5	Max Temperature of Warmest Month
BIO 6	Min Temperature of Coldest Month
BIO 7	Temperature Annual Range (BIO5-BIO6)
BIO 8	Mean Temperature of Wettest Quarter
BIO 9	Mean Temperature of Driest Quarter
BIO 10	Mean Temperature of Warmest Quarter
BIO 11	Mean Temperature of Coldest Quarter
BIO 12	Annual Precipitation
BIO 13	Precipitation of Wettest Month
BIO 14	Precipitation of Driest Month
BIO 15	Precipitation Seasonality (Coefficient of Variation)
BIO 16	Precipitation of Wettest Quarter
BIO 17	Precipitation of Driest Quarter
BIO 18	Precipitation of Warmest Quarter
BIO 19	Precipitation of Coldest Quarter

Global Digital Elevation Model

To represent the geomorphological features of the study area, a Digital Elevation Model (DEM) has been acquired from the EarthEnv repository, where spatial data are available following the work of (Amatulli et al. 2018). It has been decided to take into account the DEM parameters for the analysis and evaluation of the modelled future scenarios to compare the predicted suitable areas of the different species with the ground elevation data. By doing this overlay it was possible to exclude some areas which resulted suitable according to environmental variables, but they could not be due to above sea-level height.

Species dataset

GBIF

The Global Biodiversity Information Facility (GBIF, https://www.gbif.org/) is an international network and data infrastructure which was funded by the world's governments and with the aim to provide open access to data about all types of organisms on Earth, to everyone worldwide.

GBIF is coordinated thanks to its Secretariat in Copenhagen, and it provides institutions around the world with common standards and open-source tools; the objective is to share information about occurrences of species, in any place they have been recorded. Sources of information may be of many different kinds, from DNA barcodes to museums specimens collected in the last centuries and smartphones' photos.

Since pieces of information are derived also from museums specimens, for our study it was necessary to filter the datasets of species under investigation to remove those occurrences records; our research area is focused on occurrences along migratory routes.

MAXENT: model description and applicability

MAXENT

Maxent is a stand-alone Java software, an application used to model species niches and their distributions by applying a machine-learning technique called Maximum Entropy Modelling (https://biodiversityinformatics.amnh.org/open_source/maxent/). From a set of georeferenced occurrence localities and environmental grids, the model returns as output a probability distribution where each grid cell has a predicted suitability of conditions for the species under investigation. Therefore, the final result can be interpreted as predicted probability of presence or absence.

Models for the species are determined from a collection of climate or environmental layers, for a series of grid cells in a landscape, and a set of sample locations where there has been recorded an occurrence of that species. The model gives the suitability of each grid cell as a function of the environmental variables at that corresponding cell. The higher value of the function at a particular grid cell the higher predicted suitable conditions for that species in that associated area. The final model is a probability distribution over all the grid cells of the interested area.

The prediction consists in the expected distribution of areas that can be suitable for the presence of the species under consideration, within the future scenarios, and based on the climate model outputs.

Workflow

The collected data has been downloaded, modified, and adapted to a suitable format to be considered as an input in the model in a pre-processing workflow (.*asc* files).

As first step, the interested study area has been identified and selected within the geographical extent ranging from the coordinates: min (x = -19.3691; y = 19.3931) and max (x = 100.6309; y = 84.3931). This study area was chosen in order to understand if and, in case, how the migratory pathways of the species analysed could be modified. Given the fact that the main migratory flyway for the chosen species is the Black Sea/Mediterranean flyways, the study area was chosen to be focused mainly on the European continent, with some extent over East Asia.

The sequential phases of data-processing-work is illustrated in *Figure 4*.

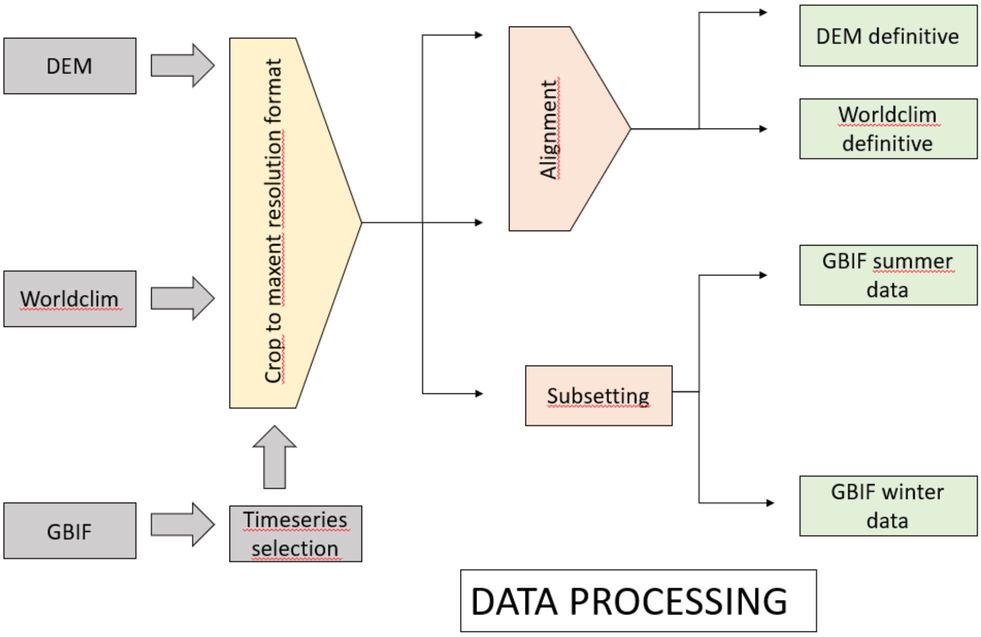


Figure 4: data processing workflow

Worldclim

Present and future projection data are downloaded from Worldclim database. The local downscaled model selected for predictions was MIROC6, associated with the SSP585 scenario. Spatial resolution used was 30 seconds.

Future predictions were divided into present (or recent past) and 4 future 20-years-period projections. The nearest 20 years from 2021 to 2040 and the following 2041-2060, 2061-2080 and 2081-2100. For each of them it has been downloaded maximum temperature parameters per month (monthly divided, 12 values) and all the estimated 19 bioclimatic variables (all the estimations were made according to the MIROC6 model).

Once all the data has been downloaded, they needed to be converted into a Maxent-usable format (asc) and cropped to the selected study area. Furthermore, climate data of 2041-60, 2061-80, and 2081-2100 have been resampled based on future climate predictions of the two decades 2021-2040. All these steps have been done using scripts in R studio environment.

DEM

R studio has been used also for cropping DEM data from EarthEnv. Moreover, DEM data needed to be aligned with the corresponding grid to make them overlap with Worldclim data.

GBIF

GBIF data has been downloaded through the GBIF package in R studio which recalls the API. The occurrences of the interested species were filtered by removing museums and zoo specimens. This selection was needed in order to visualise and maintain the occurrences of only wild specimens, otherwise occurrences would be possible in very different places inside the study area.

The data available inside the database have been filtered for years between 2015 and 2020, with the aim to analyse the latest behavioural patterns for the different species. Finally, the obtained data were cropped filtering occurrences in the interested study area. A subset of occurrences databases for each species was run returning two different data series, one for the hot season (“summer”, from April to September) and the

other for cold season (“winter”, from October to March); this Workflow has been made considering boreal hemisphere seasons.
All these steps have been done using scripts in R studio.

Maxent model run

For each species it has been predicted two future scenarios for both “summer” and “winter” seasons, for each of the four twenty-years periods.
Input data were both species occurrences points (GBIF data) plus present climate and environmental variables layers. For “summer” and “winter” seasons are selected the corresponding environmental variables, as explained above.
Training outputs and test outputs were run until the final species distribution model based on present data. To the final model, future layers of the twenty-year-periods were added giving the final prediction for the different future scenarios.
The sequential phases of the maxent model run are illustrated in *Figure 5*.

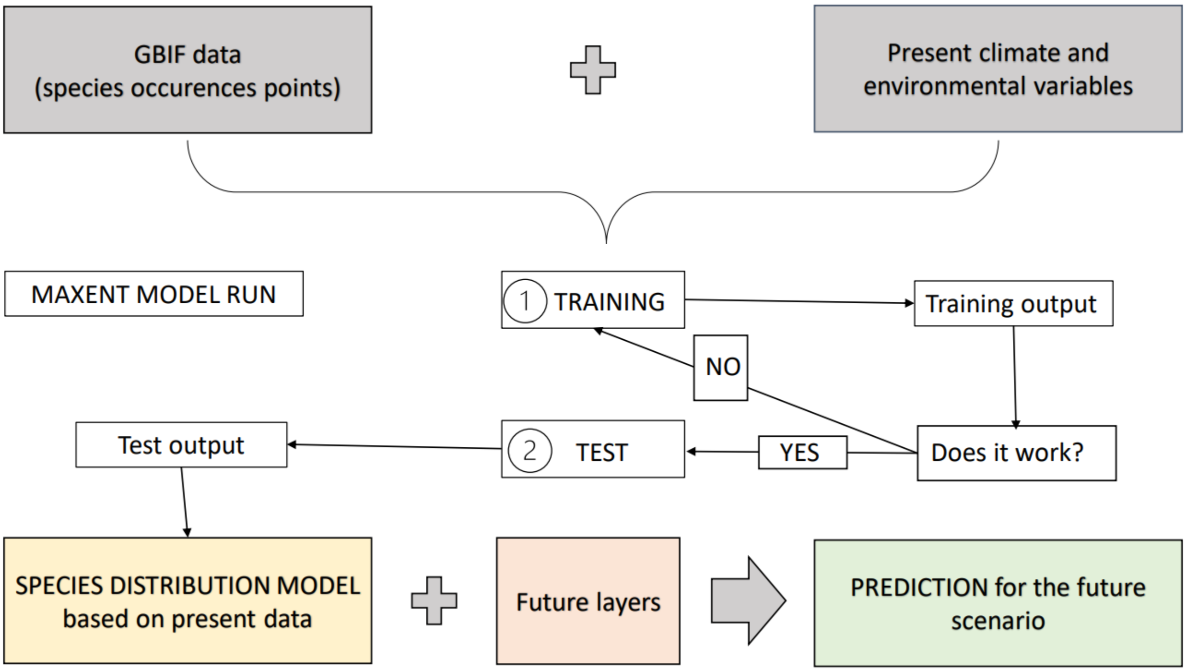


Figure 5: Maxent model algorithm to run simulations

Maxent model outcomes for each species scenarios comprehends the AUC plot, suitability maps, hotlayers climate conditions (derived from the comparison of environmental similarity of variables in resampled suitability maps with the environmental data used for training the model) and three jackknife plots (jackknife of regularised training data, of test gain, and AUC). As last step, Maxent suitability maps for present and future prediction of each species were modified using R studio.

Species in the study

The species chosen for this thesis are all members of the Family of Anatidae, Order of Anseriformes. According to the Annex II of the Birds Directive (79/409/EEC and 2009/147/EU), all of the nine species analysed are migratory huntable species. The Birds Directive requires Member States to select the most suitable sites for the conservation of species of wild birds naturally occurring in the European territory and designate them as Special Protection Areas (SPAs). Their migration pathway follows the Black Sea/Mediterranean Flyway. This migratory Flyway, part of the wader flyway for the western Palaearctic, comprises the annual migration route of wader and wildfowl populations between their breeding quarters and the wintering grounds in the Mediterranean Basin and Africa, including all stop-over sites in between. Waders using the Mediterranean Flyway breed in the arctic and subarctic region of northern Europe and Siberia, in the temperate region and also along the Black and Mediterranean Seas (Najdenski et al. 2018).
Moreover, all the selected species are typical of wetland habitats, making them particularly interesting under the ecosystem services point of view as their relevant role inside the trophic chain for wetlands, and the fact they are all huntable species, making them of economic interest too.

The nine species considered in this work of thesis are the following:

- *Anas acuta* (Northern pintail)
- *Anas crecca* (Green-winged Teal)
- *Anas platyrhynchos* (Mallard)
- *Aythya ferina* (Common pochard)
- *Aythya fuligula* (Tufted duck)
- *Mareca penelope* (Eurasian Wigeon)
- *Mareca strepera* (Gadwall)
- *Spatula clypeata* (Northern shoveler)
- *Spatula querquedula* (Garganey)

Anas acuta

Figure 6: Anas acuta male (top) and female (bottom)

Species classification inside the Red List categories (https://datazone.birdlife.org): “least concern”.

The breeding ground of the Pintail (Fig.6) covers a wide area of the northern Holarctic, across both North America and Eurasia. The Pintail is a generally migratory species and, in the majority of regions, it is a long-distance migrant. Wintering areas are spread out over a wide region, that comprehends the territories of western and southern Europe, across Africa to the Sahel, India, southwest Asia, southern China, and Japan.

Recoveries from the wintering season from December to February are found in western and southern Europe, in the area of the Black and Caspian Sea and North Africa (Arzel and Elmberg 2015). Between January and February, it can be observed an increase in recoveries in Mediterranean countries like Italy, which becomes stronger between the end of February and March. The most intensified phase of spring migration back to breeding grounds starts in March, then it becomes prominent in southern Russia in April, and finally it reaches the northernmost areas in May. On the other hand, autumn migration seems to start in August (Miller et al. 2005). Depending on the location of breeding grounds, Pintail populations follow different flyways toward wintering areas. Birds breeding in North of Europe (Iceland, Sweden, Finland, the Baltic States) and northwest Russia migrate mainly toward west and south Europe, usually along the Atlantic coast. Birds from central and western Siberia, instead, fly toward the Balkans, the Mediterranean, and the area of the Black and Caspian Sea reaching Indian country too. Some of them, can separate to southwestern and western Europe, and until West Africa territories, where weather conditions are more tropical than temperate. Finally, birds from Siberia and northern Russia flatlands may winter in southwest Asia, or the Nile Delta from where they can reach wetlands in Sudan and Ethiopia. Recoveries of ringed individuals demonstrate that it does exist an interchange between flyways in different years (MAPA, 2023). (https://www.mapa.gob.es/es/ganaderia/temas/gestion-cinegetica/kcd_speciesaccounts_2021_11_14_tcm30-652349.pdf).

Anas crecca

Figure 7: Anas crecca male (bottom) and female (top)

Species classification inside the Red List categories (https://datazone.birdlife.org): “least concern”.
The Common Teal (Fig. 7) breeding grounds cover a large area in the northern Palearctic, from Iceland to the extreme eastern part. Common Teal is mainly migratory, except some small populations living in west Europe that are resident. Wintering areas can be found in Europe, North Africa, and Asia (Giunchi et al. 2019). The main amount of recoveries come from birds ringed in Britain, Denmark, the Netherlands, and Russia. Between the winter season, the quarter of the year from December to March, recoveries are reported in a wide area of west and south Europe and in the areas between the Black Sea and the Caspian Sea (Guillemain et al. 2017). Small portions of populations cross the Sahara Desert and there are two recoveries that support this movement. Between January and February there the number of recoveries in Northern Africa decrease, while March shows an evident decrease in recoveries in Iberia with a consequent increase in Northern Italy. The speed of spring migration appears to increase significantly during April, directed northeast on a broad front. Autumn migration seems to start around July and August, going on until October (Giunchi et al. 2019). The direction of autumn migration of Common Teal is southwest, and there have been reported different flyways parallel to each other. The populations breeding at ground sites on the East of the Ural Mountains and in Siberia spend wintering period in the Caspian Sea, the Black Sea, and the eastern Mediterranean area. Some populations are known to follow the Nile River south to the African Horn (MAPA, 2023).

Anas platyrhynchos

Figure 8: Anas platyrhynchos male (bottom) and female (top)

Species classification inside the Red List categories (https://datazone.birdlife.org): "least concern".

The mallard (Fig.8) is the most widespread and numerous dabbling duck in the world. It is, therefore, often used as a model species for harvest management, ecological processes research, and disease. In North America, Europe, and Asia most mallard populations are migratory, and they rely on suitable stopover sites along their flyways (Bengtsson Daniel and Avril 2014).

Breeding grounds of the Mallard covers a wide area of the Holarctic, across both Eurasia and North America. It has been studied that populations of birds breeding in temperate regions are mainly sedentary, while birds breeding in northern areas, places where in winter open waters are hard to find, are migratory. Mallard winters across central Asia and in a large area over Europe. The majority of recoveries come from birds ringed in Russia, Sweden, the Netherlands, Denmark, and Britain, although extensive ringing of Mallards has been carried out in a lot of countries. During winter season, from December to February, recoveries are highly concentrated from southern Sweden to south-west countries, but many of them are also reported in south Europe, as well as in the area of the Black and the Caspian Sea. Between January and February, it can be observed recoveries start to decrease in Mediterranean countries like France and Italy; between February and March this trend gets stronger involving Iberia as well. The most intense phase of spring migration takes place between March until May in the most northern regions. During breeding season, Mallards can be found in the majority of Europe, including the northernmost areas, with east borders corresponding with Russia flatlands. In August it starts wintering migration which continues until November.

Various flyways have been recognised; birds breeding in northeast Europe (Russia, Finland, Sweden, and the Baltic states) migrate to wintering areas located in west Europe, Britain, and Ireland. Mallard populations from central and eastern Europe migrate southeast or south to the Black Sea or to the Mediterranean. Mallards that breed in central Russia, western Siberia and Kazakhstan migrate to the Caspian Sea, the Black Sea, and east Mediterranean, but they also reach territories south to Iran-Afghanistan. Finally, relevant amount of males from breeding grounds in Ukraine until west Siberia are known to gather in the Caspian Sea and Volga delta during moult (MAPA, 2023).

Aythya ferina

Figure 9: Aythya ferina male (right) and female (left)

The Common Pochard (Fig. 9) is a differential and partial migratory freshwater diving duck. It means that one part of the population is migratory while the other fraction is sedentary; moreover, females migrate farther south than males (Folliot et al. 2018). Starting from the middle of the 18th century, Common Pochard has experienced a relevant expansion of its breeding grounds range both westwards and northwards towards Scandinavia and northwestern Europe and, during the last twenty years, Common Pochard spread over Mediterranean countries and the Maghreb region. As the breeding range expanded, the number of wintering individuals among this flyway gradually increased until the end of the 20th century (A D Fox et al. 2016). However, the number of wintering individuals experienced a strong recent decline, recorded in most countries of the flyway, and, unfortunately, it is predicted to continue also in the foreseeable future. For this reason, this species is considered as "vulnerable" according to the Red List categories (https://datazone.birdlife.org).

The Pochard breeding grounds are located in the Palearctic, from western Europe to north-eastern China. It is present throughout the whole year in western and southern Europe, but otherwise this species is highly migratory. Wintering regions spread out from western Europe through Japan until southern Asia. The Pochard is widespread across central and northwestern Europe during winter months, with highly concentrations in the UK, France, Germany, and The Netherlands. Other relevant concentrations occur in countries around the Black Sea and Caspian Sea. In north Africa, only few populations are found during winter, and very small numbers at souths of the Sahara. Few individuals of Pochard have been ringed in most countries with the largest amount of recoveries come from ringed birds in Britain, Switzerland, and Russia (Folliot et al. 2018). During winter period December - February major recoveries are reported in western and southern Europe, as well as in Denmark and southern Sweden, with some evidence also in northwest Africa. Between January and February, an overall decrease in recoveries from Western and Mediterranean Europe is registered, and it becomes more intense in March; migration toward breeding grounds continues in Russia and the east of Europe until May. Recoveries from the breeding season, from May to June, are obeserved from west Europe to Russia (Folliot et al. 2018). A high concentration of recoveries can be found in the Ob-Irtysh basin, the north of Kazakhstan and on the east of the Urals. Autumn migration starts in August and even in October can still be find small numbers of birds in Russia. Pochards having breeding grounds in central and northern Europe migrate to wintering areas in west Europe. From west and central Russia, populations migrate to west Europe and Britain, while pochards breeding in Kazakhstan and southwest Siberia move to the Black Sea, Caspian Sea, and west to Italy. Finally, pochards breeding in Central Asia and Siberia spend wintering season in southwest Asia (MAPA, 2023).

Aythya fuligula

Figure 10: Aythya fuligula male (top) and female (bottom)

Species classification inside the Red List categories (https://datazone.birdlife.org): “least concern”.

The Tufted Duck (Fig. 10) breeding grounds are spread out across northern Eurasia, from Iceland to the Bering Sea. A huge percentage breed in Russia and neighbouring Fennoscandia. This is a mainly migratory species, but there are some populations in Europe which are resident or only perform short-distance movements. Wintering areas are located in northwestern and south Europe, over the territories of the Caspian and Black Seas, northern Africa, across the whole Asia to the Far East, Japan. Ringing of *Aythya fuligula* in Europe has not been widespread; the largest amount of recoveries available come from Britain, Switzerland, and Denmark (Y. Liu et al. 2012). During winter season, from December to February, recoveries are concentrated in west and central Europe, as well as in southern and western Baltic area. Between January and February, a decrease in recoveries from South-West of France and Iberia is recorded; moreover, this tendency becomes more intense between February and March. During April and May, mainly, take place the most intense phases of return migration (Y. Liu et al. 2012). During the breeding season from May to June, recoveries are spread out in northern Europe and eastward to the Urals. In addition, during this season some recoveries are also found in central and west Europe, including Iceland. The migration toward wintering areas continues until October and, by November, the majority of Tufted Ducks have left the Russian breeding areas. Birds breeding in Scandinavia peninsula, the Baltic countries and northwest Russia migrate to western and central Europe, while some populations also reach southwestern Europe. From western Siberian and central Russia, populations migrate to the Black Sea and Caspian Seas, east Mediterranean and central or eastern Europe. Moreover, some populations breeding in Siberia and in the eastern part of the breeding range, spend winter season in the Caspian region, Pakistan, northern India, and southeast China to Japan (MAPA, 2023).

Mareca Penelope

Figure 11: Mareca penelope male (top) and female (bottom)

Species classification inside the Red List categories (https://datazone.birdlife.org): “least concern”.

Eurasian Wigeon (Fig. 11) covers a wide breeding area over northern latitudes in the Palearctic, which is located from Iceland in the west to the Bering Strait in the east. Except for some small populations in western Europe, the majority of populations are highly migratory, since wintering areas range from Europe in the west to southern Asia and Japan eastward. Only few individuals are found south of the Sahara Desert in wintering period, in particular in the East African Rift Valley (Panov et al. 2023). Most of recovered Eurasian Wigeon have been ringed in western Europe, especially Britain and The Netherlands. High numbers are found in west Europe during wintering months, from December to March. In addition, recoveries are also registered in south Europe and eastwards to the Black and the Caspian Seas. In April occur the most intense phases of migration back to breeding grounds through southern Russia (Bouchaala et al. 2017). Across the breeding season from May to June, recoveries of *Mareca penelope* are reported from Iceland, west Europe, Fennoscandia, and Russia. Autumn migration continues until October and seems to follow a more northerly route than during spring migration. Migration back to wintering areas seems to follow a more direct route across central Europe. Birds breeding in Siberia spend winter season along Mediterranean coasts, as well as the Caspian Sea and the Black Sea coastlines. Finally, birds spending wintering period in west Europe continue further south during more severe winters. Since there is evidence of some recoveries in southern Russia and in Kazakhstan in autumn, they might be a result of moult migration of males and non-breeders (MAPA, 2023).

Mareca strepera

Figure 12: Mareca strepera male (top left) and female (bottom right)

Species classification inside the Red List categories (https://datazone.birdlife.org): “least concern”.

The Gadwall (Fig. 12) is a Holarctic species whose breeding grounds are found locally in Europe, in northwestern North America, and eastwards to northern China. This is a largely migratory species, but mainly resident in western and southern Europe. The number of ringed individuals in most countries is not so high, with the largest amount of recoveries coming from birds ringed in Russia, Germany, The Netherlands, and Britain. During wintering season, from December to February, recoveries are concentrated in western Europe, with some exception also reported in the Mediterranean and the Caspian Sea territories. Few recoveries are reported during March, while in April many recoveries are spread out in Kazakhstan and southern Russia (Kohl et al. 2022). Over the breeding season period, recoveries are reported in western and central Europe as well as from southern Russia to east and southwestern Siberia. Recoveries number increases in western Europe from September to November, while most birds in Russia have already flown to coastal areas of the Caspian and Black Seas. Birds breeding in Britain, Denmark, Poland, Fennoscandia, Baltic countries, and European Russia migrate to western Europe and the Mediterranean coasts (Arzel and Elmberg 2015). Population breeding in eastern and central Europe s well as southwestern Siberia, spend the wintering season in the area of eastern Mediterranean Sea, Black and Caspian Seas, Turkey and south to the Nile, with small number of individuals reaching East Africa territories. From breeding grounds in Siberia, Gadwall populations migrate to winter also in the Caspian Sea, Uzbekistan, Turkmenistan, Pakistan and India (MAPA, 2023).

Spatula clypeata

Figure 13: Spatula clypeata male (top left) and female (bottom right)

Species classification inside the Red List categories (https://datazone.birdlife.org): “least concern”.

Shoveler (Fig. 13) breeding grounds cover a wide geographic region over northwestern North America and a large area in northern Eurasia. On the other hand, wintering areas spread out from western and southern Europe to southern Asia eastwards until Japan (Khemis et al. 2017). In Europe, populations tend to concentrate in the southern countries of Spain and France, as well as eastwards into Turkey and Greece. Moreover, further concentrations occur in the Caspian Sea area and in southern Iran. The highest amount of recoveries come from individuals ringed in Britain, the Netherlands, and Russia. Recoveries during winter period between December and February can mainly be found in western and south-western Europe and in northwest Africa. Small numbers of recoveries are also registered eastwards to the area of Caspian Sea. Between January and February, it can be observed a tendency to decrease in the number of recoveries from Iberia and Italy, while the intensity of migration movements back to breeding grounds increases in March, with a further decrease in Iberia and significantly high influxes of migrants in Italy (Hill et al. 2021). In April, recoveries are observed to spread out in southern Russia and Kazakhstan, while in May birds are reported from northward areas. Migration toward wintering areas starts early in autumn, as many birds start migrating west in August. Large concentrations are reported along the Atlantic coast between September and November months. The presence of small numbers of recoveries in Italy during autumn might confirm the hypothesis that species performs a loop migration. *Spatula clypeata* individuals breeding in northern Europe and northwestern Russia fly south- westwards to western and southwestern Europe (Khemis et al. 2017). Birds from Britain and Ireland winter south to Spain and France, while birds breeding at grounds located in central and eastern Europe winter in western Europe and the Mediterranean coasts. From Siberia, Russia, and Kazakhstan birds migrate to Mediterranean basin or to the Caspian area, or to East Africa; some populations follow a different migratory route which brings them to winter in southwest Asia territories as well as further south to Pakistan and India (MAPA, 2023).

Spatula querquedula

Figure 14: Spatula querquedula male (left) and female (right)

Species classification inside the Red List categories (https://datazone.birdlife.org): "least concern".

Garganey (Fig. 14) breeding grounds cover a large area in Palearctic, from west Europe to eastern Asia especially between 42°N and 65°N. It is a highly migratory species: its main wintering areas are located across tropical Africa south of the Sahara, in southern Asia and India. In Africa, it spends wintering period along a line of approximately 10- 15°N from Chad to Senegal, with smaller ringed records found in Horn of Africa (Khemis et al. 2017). *Spatula querquedula* populations are localised and sparsely distributed during breeding season, with the exception of a few sites in Russia; indeed, they have been ringed in small numbers in the majority of European countries (Kohl et al. 2022). Highest numbers of recoveries come from ringing performed in Russia and the Netherlands. During winter, most of the recoveries have been reported in southern Europe, especially in Italy and the Balkan region. Few recoveries have also been registered from the Sahel region, mainly in Senegal and Mali. The number of Garganey spending winter season in Europe is small compared to the amount of individuals crossing the Mediterranean Sea to reach areas south of Sahara Desert. Reporting recoveries chances from individuals that stay in Europe is higher than for those which cross Mediterranean Sea during their migratory route; this is likely due to the mismatch between the number of recoveries against the number of wintering birds. Mediterranean crossing pathway is evident from the increase in recoveries in Italy between January and February; along with Greece and the Balkans, Italy is involved in strong return movements in March and, with a decrease in April, in correspondence with the absence of recoveries reported from the African winter quarters (Hill et al. 2021). Back to breeding grounds migration continues in April and further north in May toward southern Russia and Kazakhstan. For breeding season recoveries are spread out from Siberia to west Europe. Autumn migration begins in August even though some populations are still reported in Russia in October. Birds that have breeding grounds in western and northern Europe follow two main routes; once pass through the Iberian Peninsula while the second one stretches out directly over central Mediterranean, on their way to West Africa, via Morocco or Algeria respectively. Birds breeding in Eastern European areas pass over eastern Mediterranean coasts on their way to East Africa. Also birds coming from Siberian wetlands cross eastern Mediterranean and Middle East on their way to East Africa, until Chad on the farthest west. On the other hand, some of them migrate over eastern Iran on their way to Pakistan, India, and Sri Lanka. Central Mediterranean Sea is the focal area from both West and East Africa population on their return migration. This apparent loop flyway is supported by the huge number of recoveries registered in Italy between February and April (MAPA, 2023).

Results

Anas acuta (Northern Pintail)

Present vs. forecasted summer

Suitability maps

The Maxent model for the distribution in summer for the species *Anas acuta* resulted in an Area Under Curve (AUC) of 0.712, testifying a good predictive performance. In *Figures 15a-e* are grouped the present projection and the four projections based on environmental variables predicted evolution for every twenty-years-period. These plots are the outputs of R studio conversion process from the *.asc* file given by Maxent model into a *.png* file, with higher resolution quality and larger spectrum of colours, with the aim to make the results better understandable.

Since the very first future prediction, for the nearest future twenty-year period, it is already possible to see a predicted gradual shift of areas with better suitability to the territories of northern Europe, the North-Russia coastline, the Murmansk peninsula, and Novaja Zemlja and Svalbard islands. Going on toward the projections of more distant futures, it is observable the intensification of warmer colours in these regions; in particular, red and orange areas cover the majority of the Arctic Ocean islands and northern coasts of East-Russia and Scandinavian peninsula, as well as the coasts Iceland and a small portion of Greenland. Finally, it can be noticed that the blue colour of the central coastal areas of Russian country turns into light green shades.

In parallel, it seems that some regions will be less suitable for this species, changing from being coloured in green to blue. Among them, in particular there are changes for Greece, Anatolian peninsula, the Caucasian region and arid territories of Kazakhstan.

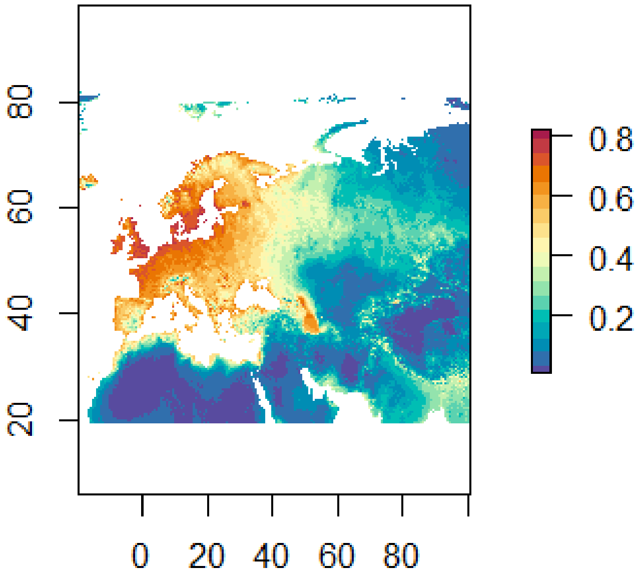


Figure 15a: Suitability map output for present summer probability distribution for Anas acuta

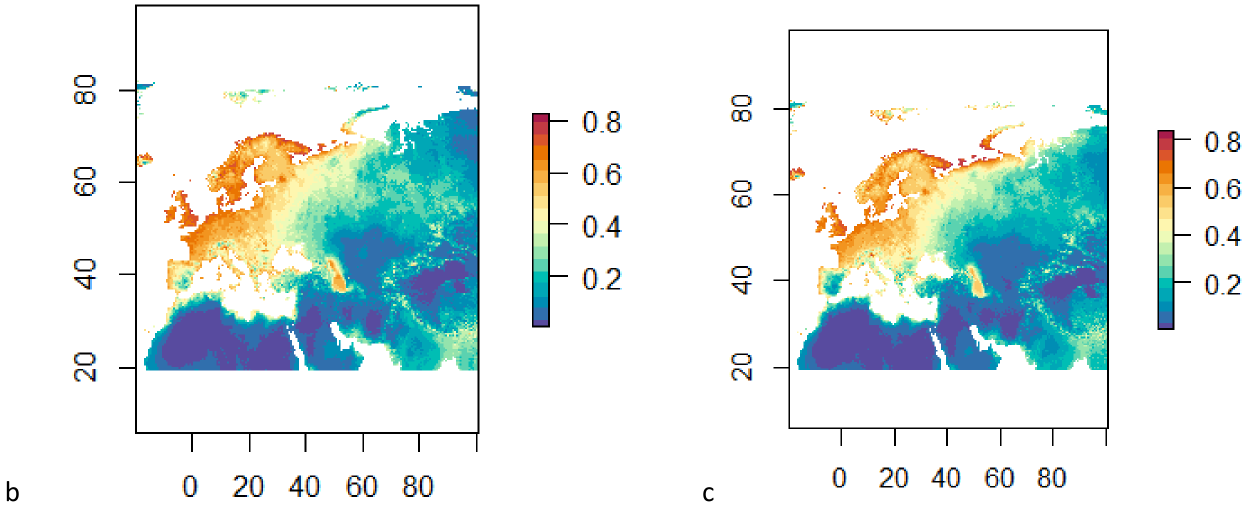


Figure 15b and 15c: Results of the simulation for summer 2021-40 (b) and 2041-60 (c)

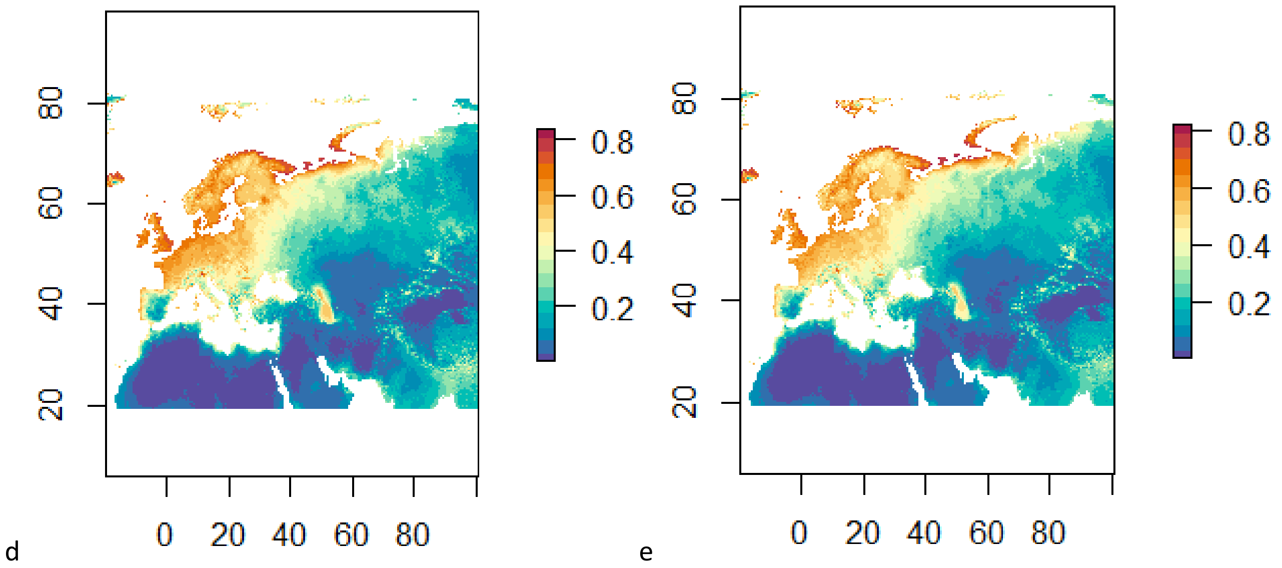


Figure 15d and 15e: Results of the simulation for summer 2061-80 (d) and 2081-2100 (e)

Novel points

In the following picture (Fig. 16), the environmental similarity of predicted variables in resampled scenario is compared to the environmental data used for training the model. During projections pathways prediction variables can assume values outside the training range; these predictions are called novel climate conditions, and they are represented with red colour. Predictions in red areas should be treated with strong caution because those areas have one or more environmental variables outside the range present in the training data. Therefore, if at least one environmental variable exceeds the suitable range of physiological parameters that characterises the fitness of *Anas acuta* species, that area is predicted for not being suitable anymore. On the other hand, the bluer a geographical region, the higher the overlapping of all the variable parameters, making that region particularly suitable, under a climatic and weather perspective. What can be seen in this picture is an intense blue colour pattern in central and east Europe, in general along the Baltic Sea coastal areas and west-Russia territories. But some blue areas are also noticeable in the north of France, some places in Spain, and the Po valley. By contrast, the regions coloured in red correspond mainly to arid and desert habitats.

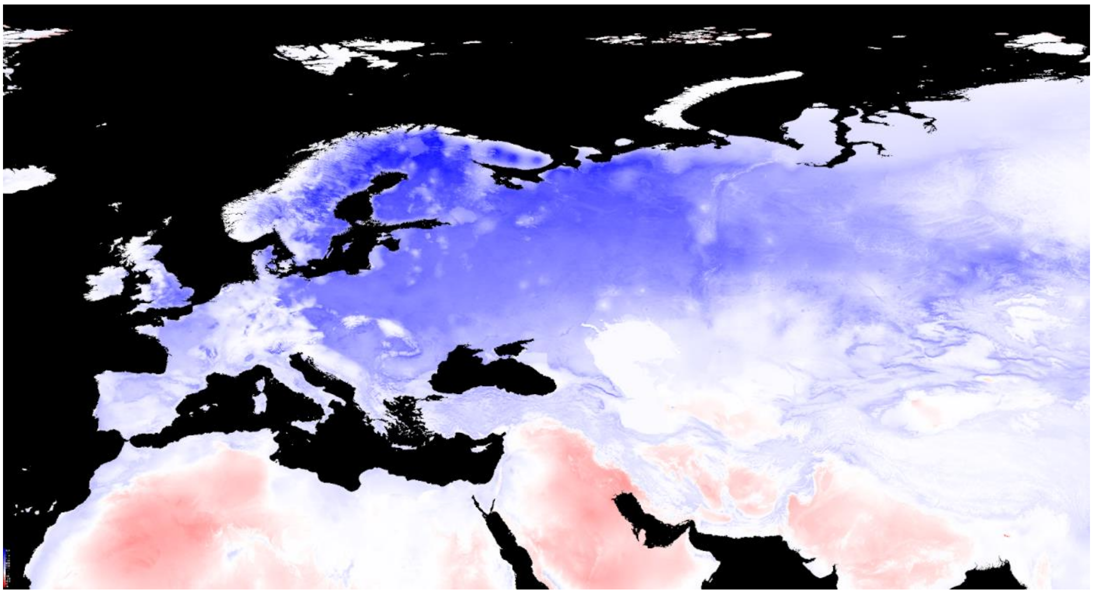


Figure 16: novel point in the hotlayers climate conditions: summer 2081-2100

Present and forecasted winter

Suitability maps

The Maxent model for the distribution in winter for the species *Anas acuta* resulted in an Area Under Curve (AUC) of 0.675, testifying a good predictive performance. In the following figures (Fig. 17a-e) present winter and predicted future conditions are compared. At present situation, it is predicted highest suitable condition in south-central Europe, territories around Caspian Sea, India, and Indian Ocean coastal areas. As for summer scenarios, there is observed an increase of warmer coloured areas at high latitudes, and the Arctic Ocean islands that, at present conditions, are almost totally painted in blue. In territories on the north of Norway and Finland there still exist a portion of blue areas for the 2081-2100 predicted scenario. Moreover, green colour expands their presence over Russian flatlands. Finally, green-to-yellow colour characterises coastal areas of Iran, Pakistan, and India.

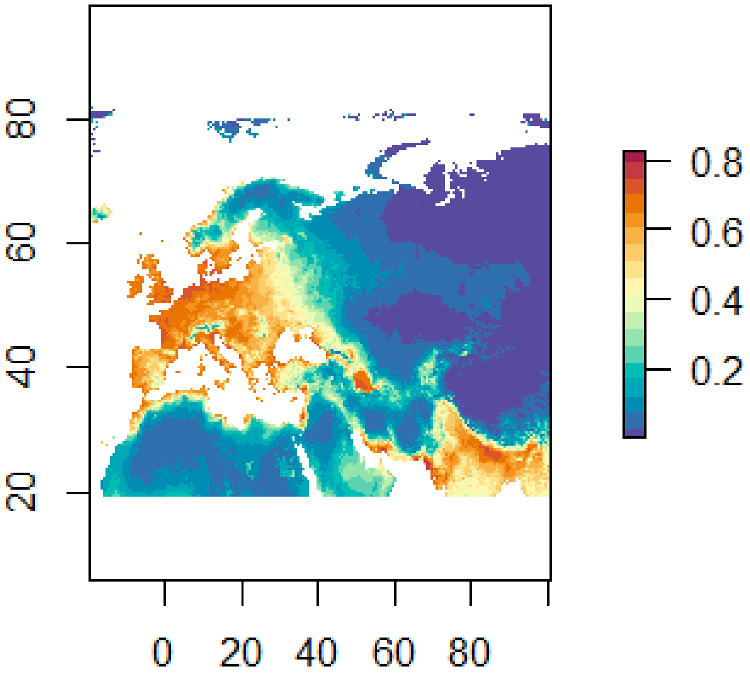


Figure 17a: representation of the Maxent model for present situation

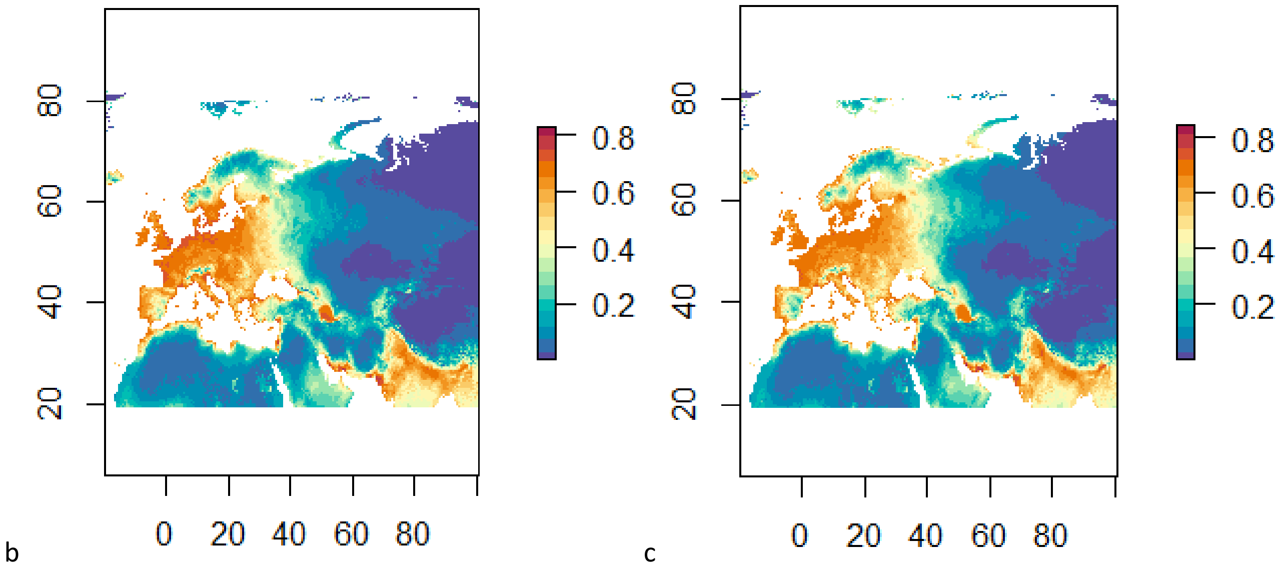


Figure 17b and 17c: Results of the simulation for winter 2021-40 (b) and 2041-60 (c)

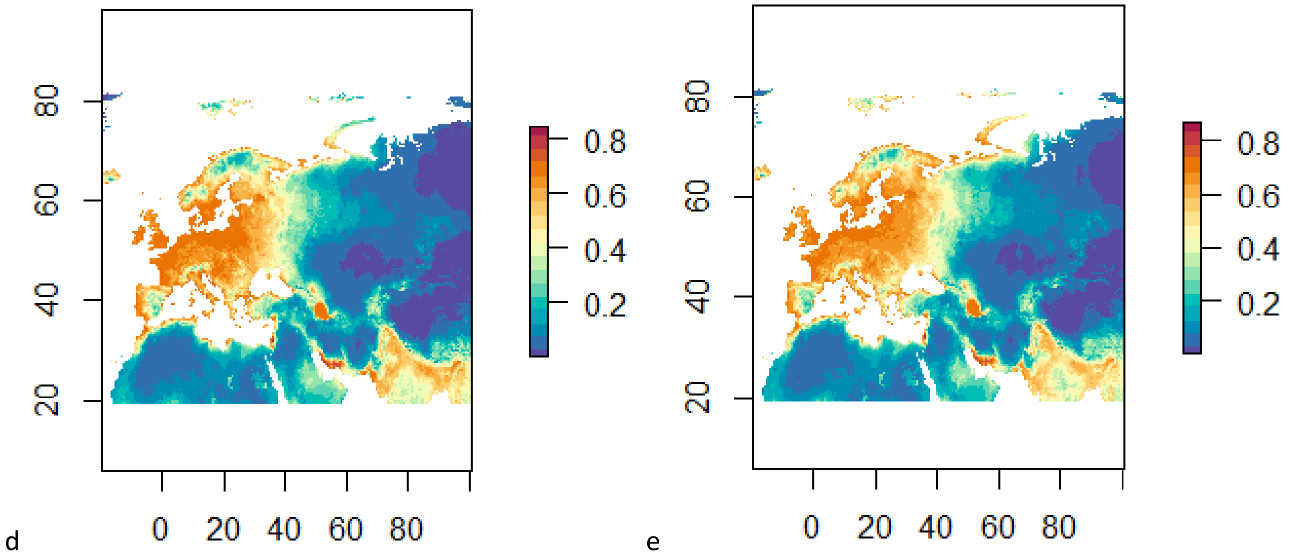


Figure 17d and 17e: Results of the simulation for winter 2061-80 (d) and 2081-2100 (e)

Novel points

In *Figure 18* it can be noticed that, compared to the previous picture of summer period, the dark blue region (where it is higher the number of climatic variables that overlap) is shifted mainly in central-East Europe, therefore to southern latitudes. A lot of territories in France, south of England, North of Spain and Italian valleys are predicted to be very suitable as well. To these also Russian flatlands are predicted to meet parameters for an increasing number of variables.

On the other hand, red places seem to correspond with the same chart of the summer period and, moving toward further futures scenarios, red colour becomes darker. While in Europe this plot is consistent with predicted suitability conditions, some red areas appear over India, Iran, and Pakistan coastal areas. Since this plot indicates red colour areas where at least one environmental variable exceeds the thresholds of physiological parameters necessary for the fitness of the species, there is a discrepancy between this chart and the suitability maps, which, by contrast, predicted favourable conditions in those areas. In particular there is the region of the Strait of Hormuz which seems very suitable according to the suitability scenario's plot but coloured in red in the novel layer plot.

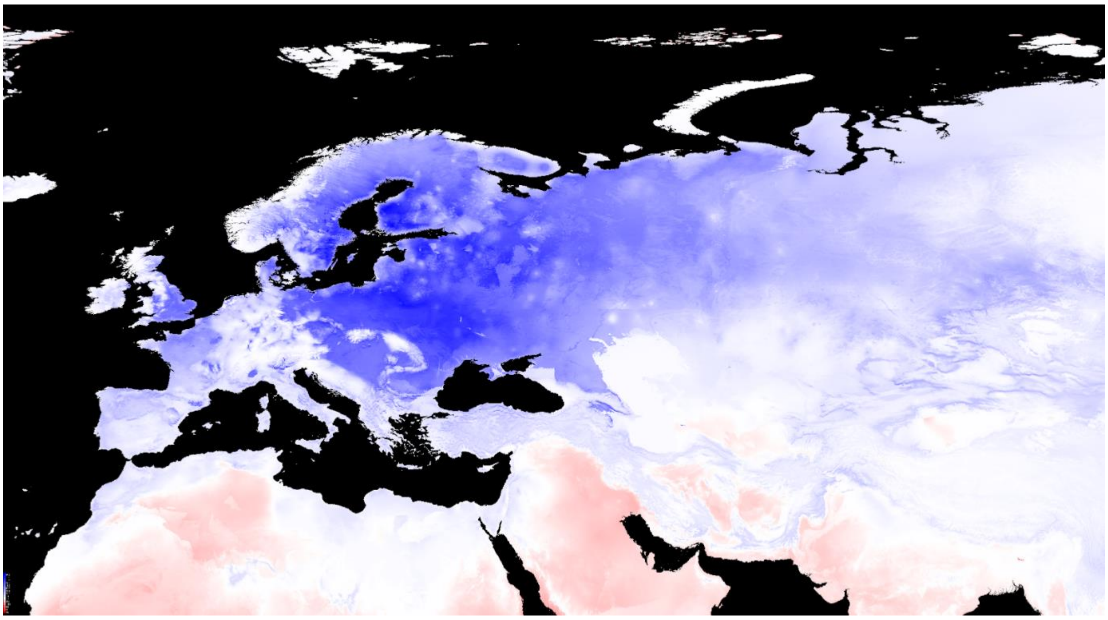


Figure 18: novel point in the hotlayers climate conditions: winter 2081-2100

Anas crecca (Green-winged Teal)

Present and forecasted summer

Suitability maps

The Maxent model for the distribution in summer for the species *Anas crecca* resulted in an Area Under Curve (AUC) of 0.592, testifying a good predictive performance. In the following figures (Fig. 19a-e) present summer and predicted future conditions for *Anas crecca* species are compared. It is observed an increase of warmer coloured areas at high latitudes, and the Arctic Ocean islands that, at present conditions, are coloured with light blue and green. Moreover, green colour expands their presence over Russian coastal and more continental areas. Finally, green-to-yellow colour characterising coastal areas of Iran, Pakistan, and India, disappear in predicted scenarios (these regions are therefore expected to become less suitable). The same predicted pathway is observed for Iberic peninsula. In general, it can be observed that suitable conditions are more or less equally spread all around European countries.

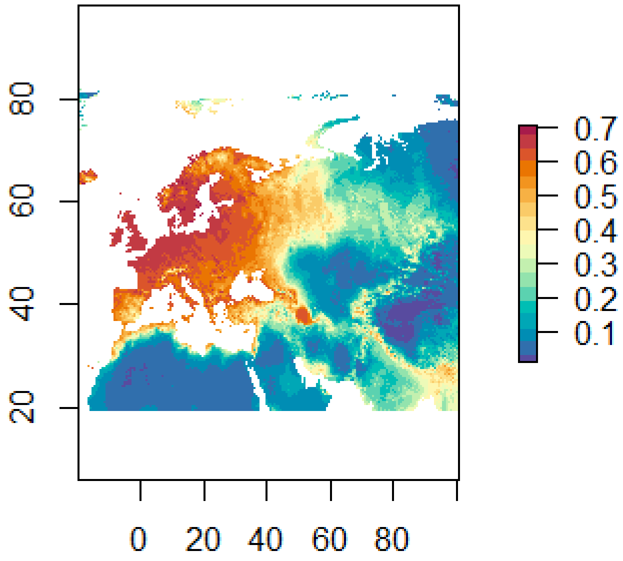


Figure 19a: representation of the Maxent model for present situation

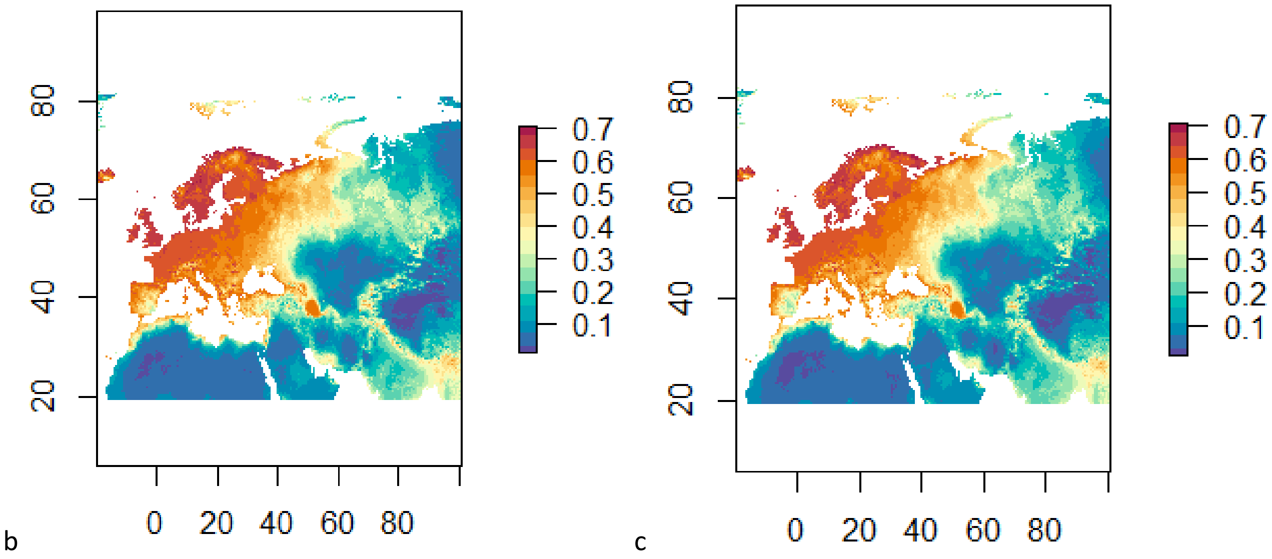


Figure 19b and 19c: Results of the simulation for summer 2021-40 (b) and 2041-60 (c)

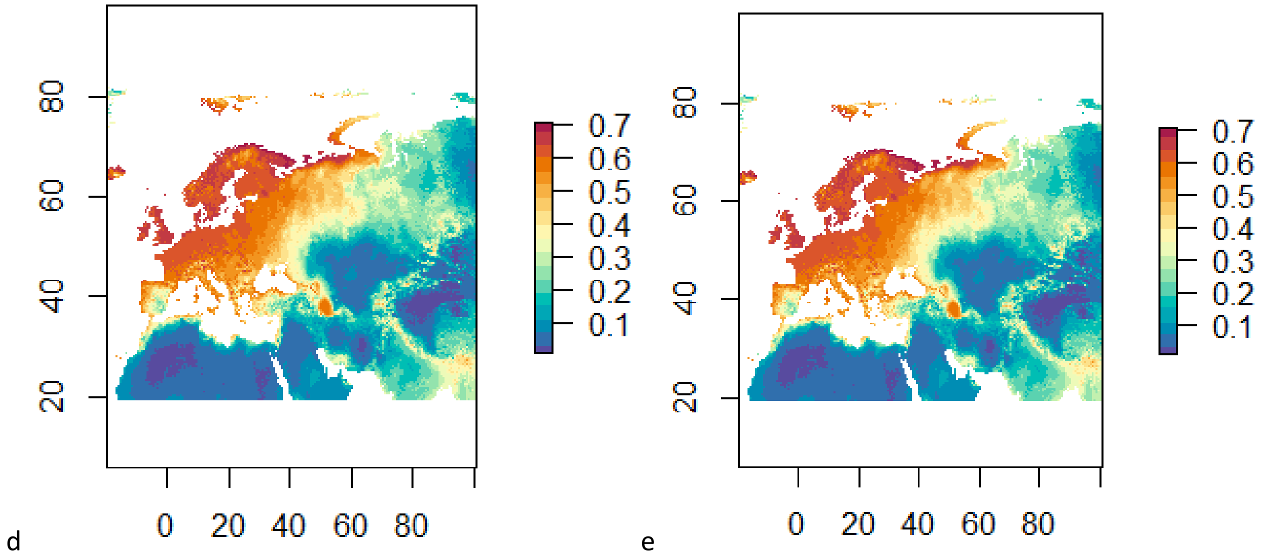


Figure 19d and 19e: Results of the simulation for summer 2061-80 (d) and 2081-2100 (e)

Novel points

In *Figure 20* it can be noticed that the dark blue region (where it is higher the number of climatic variables that overlap) is located mainly in Scandinavia and Russian coastal areas. In general, it seems the best climatic conditions will be found in north-east Europe territories.

Red places correspond with arid-to-desertic territories, and they become darker and darker moving toward further predicted scenarios.

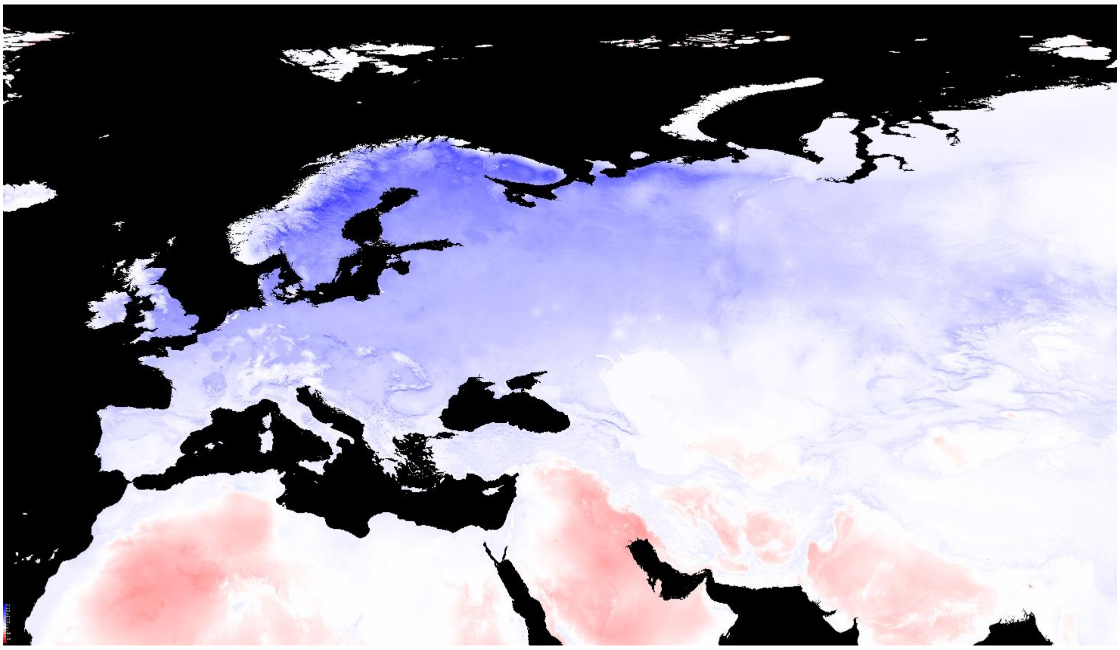


Figure 20: novel point in the hotlayers climate conditions: summer 2081-2100

Present and forecasted winter

Suitability maps

The Maxent model for the distribution in winter for the species *Anas crecca* resulted in an Area Under Curve (AUC) of 0.599, testifying a good predictive performance. In the previous figures (Fig. 21a-e) present winter and predicted future conditions are compared. As for summer scenarios, it is observed an increase of warmer coloured areas at high latitudes, and the Arctic Ocean islands that, at present conditions, are almost totally painted in blue. Moreover, green colour expands their presence over Russian flatlands. Finally, green-to-yellow colour characterises coastal areas of Iran, Pakistan, and India.

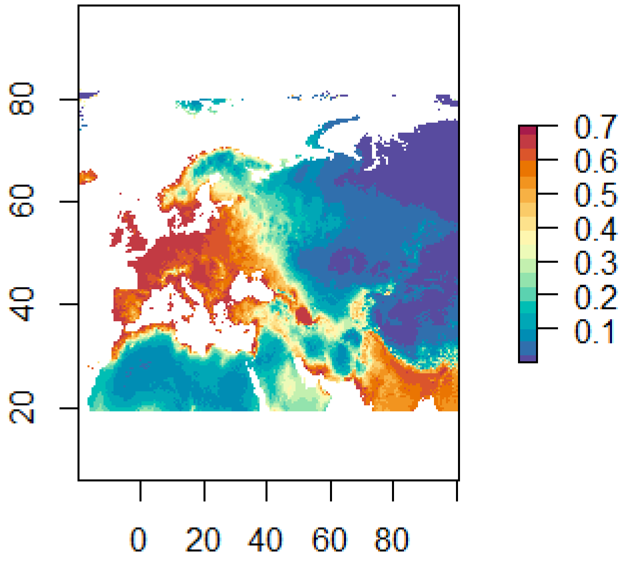


Figure 21a: representation of the Maxent model for present situation

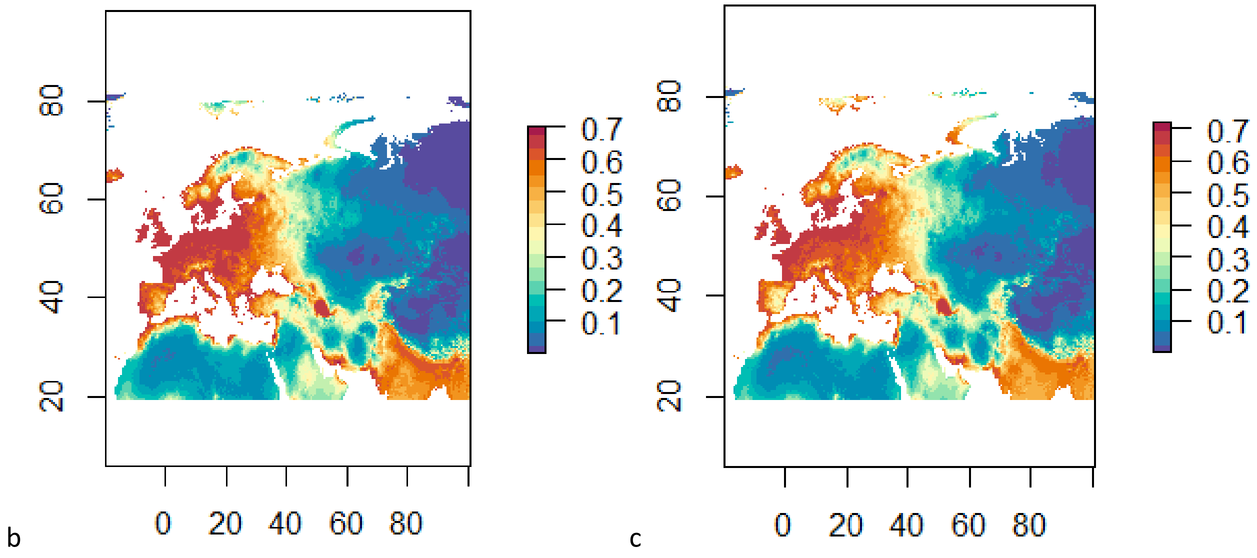


Figure 21b and 21c: Results of the simulation for winter 2021-40 (b) and 2041-60 (c)

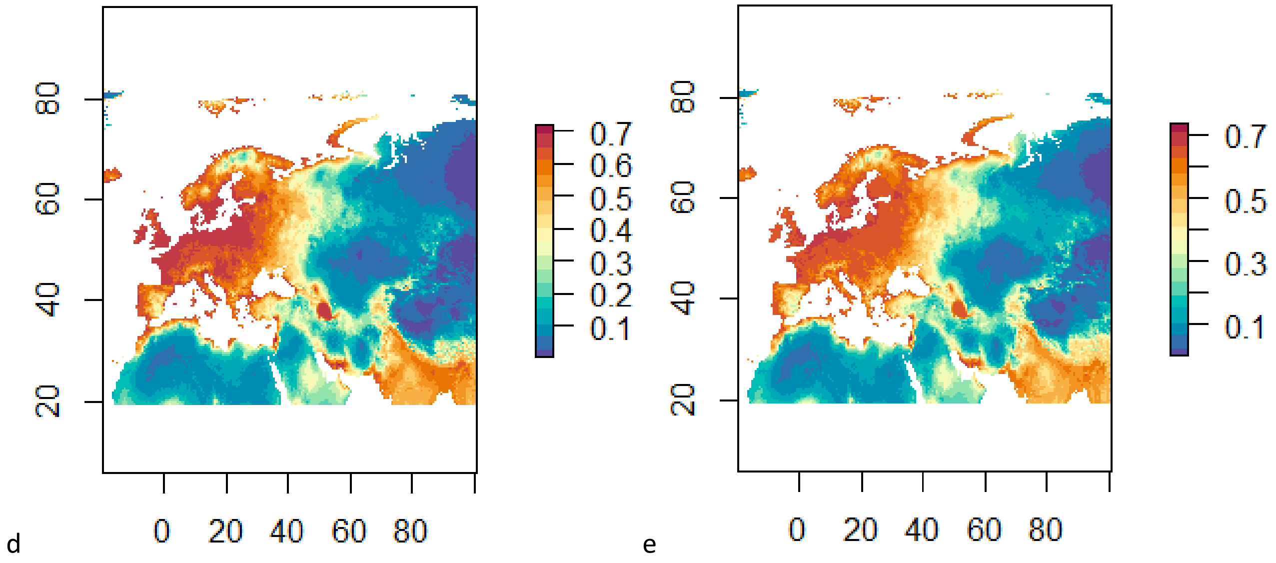


Figure 21d and 21e: Results of the simulation for winter 2061-80 (d) and 2081-2100 (e)

Novel points

In *Figure 22* it can be noticed that, compared to the previous picture of summer period, the dark blue region is shifted mainly in central-East Europe, all around the Baltic sea, therefore to southern latitudes. A lot of territories in the south of England, and Italian valleys are predicted to be very suitable as well. To these also Russian flatlands are predicted to meet parameters for an increasing number of variables.

On the other hand, red places seem to correspond with the same chart of the summer period and, moving toward further futures scenarios, red colour becomes darker. While in Europe this plot is consistent with predicted suitability conditions, some red areas appear over India, Iran, and Pakistan coastal areas. Since this plot indicates red colour areas where at least one environmental variable exceeds the thresholds of physiological parameters necessary for the fitness of the species, there is a discrepancy between this plot and the suitability maps, which, by contrast, predict favourable conditions in those areas. In particular, there is the region of the Strait of Hormuz which seems very suitable according to the suitability scenario's plot but coloured in red in the novel layer plot.

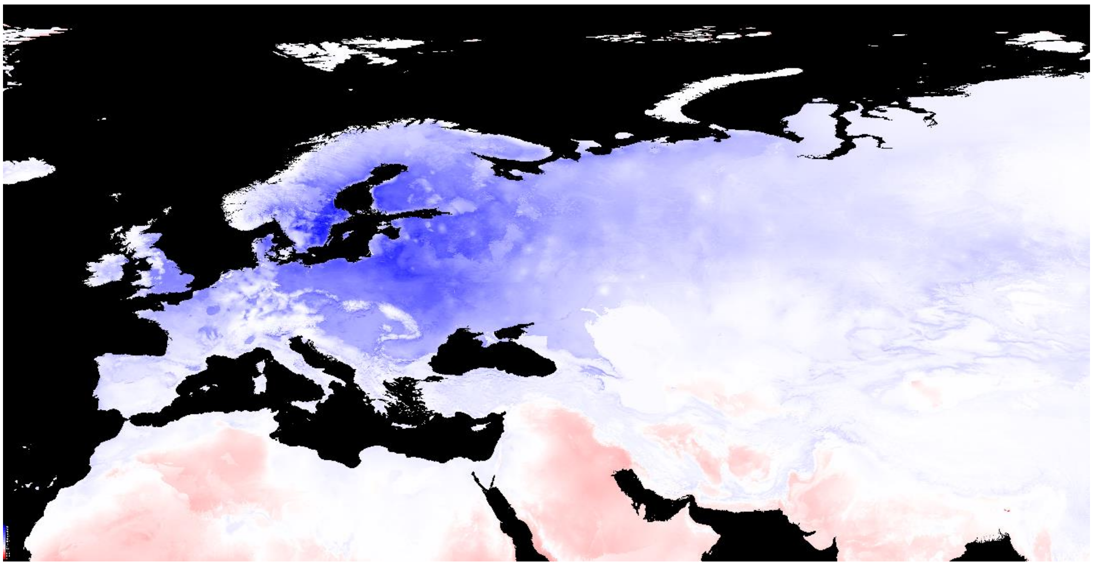


Figure 22: novel point in the hotlayers climate conditions: winter 2081-2100

Anas platyrhynchos (Mallard)

Present and forecasted summer

Suitability maps

The Maxent model for the distribution in summer for the species *Anas platyrhynchos* resulted in an Area Under Curve (AUC) of 0.532, testifying a good predictive performance. In the following figures (Fig. 23a-e) present summer and predicted future conditions for *Anas platyrhynchos* species are compared. It is observed an increase of warmer coloured areas at high latitudes, and the Arctic Ocean islands that, at present conditions, are green-coloured. Since this species is already widely diffused, the result from the probability distribution maps is consistent with the low value returned from the AUC plot. All the territories of Europe and the whole east of Russia are painted with green-to-yellow colours. For this species, changes in climatic variables seem to not affect its distribution through the European continent.

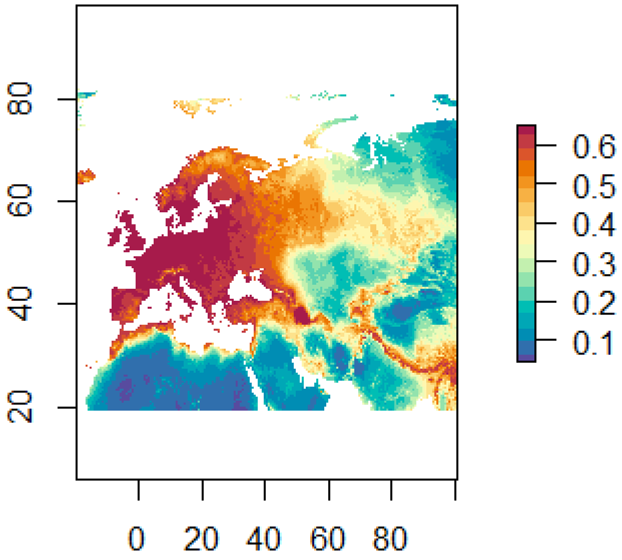
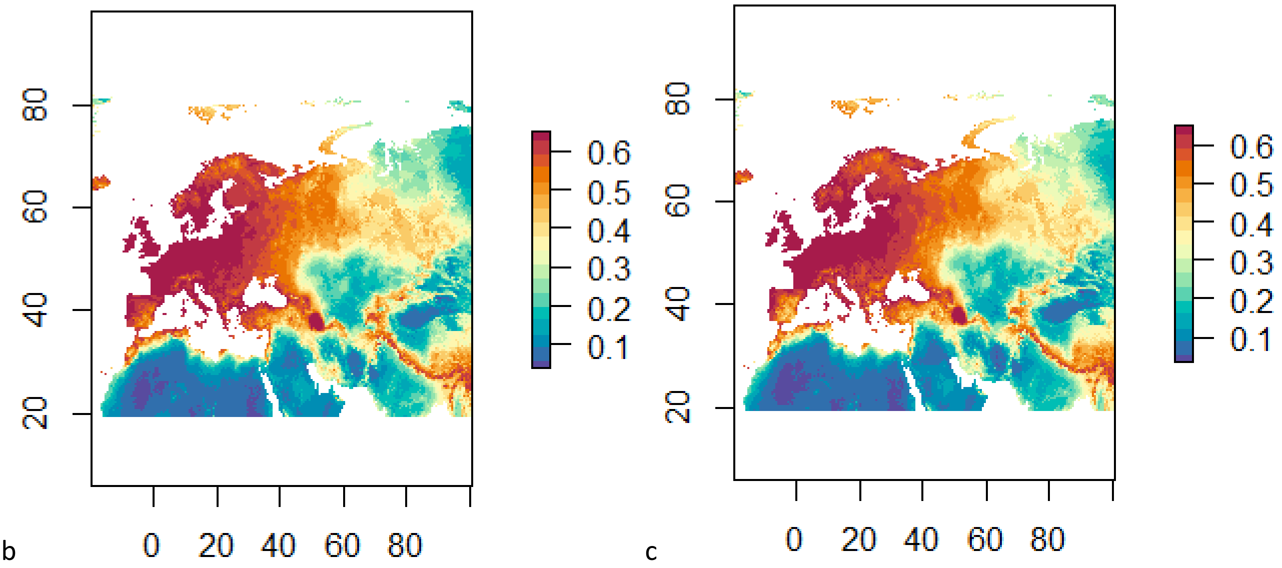


Figure 23a: representation of the Maxent model for present situation



b

c

Figure 23b and 23c: Results of the simulation for summer 2021-40 (b) and 2041-60 (c)

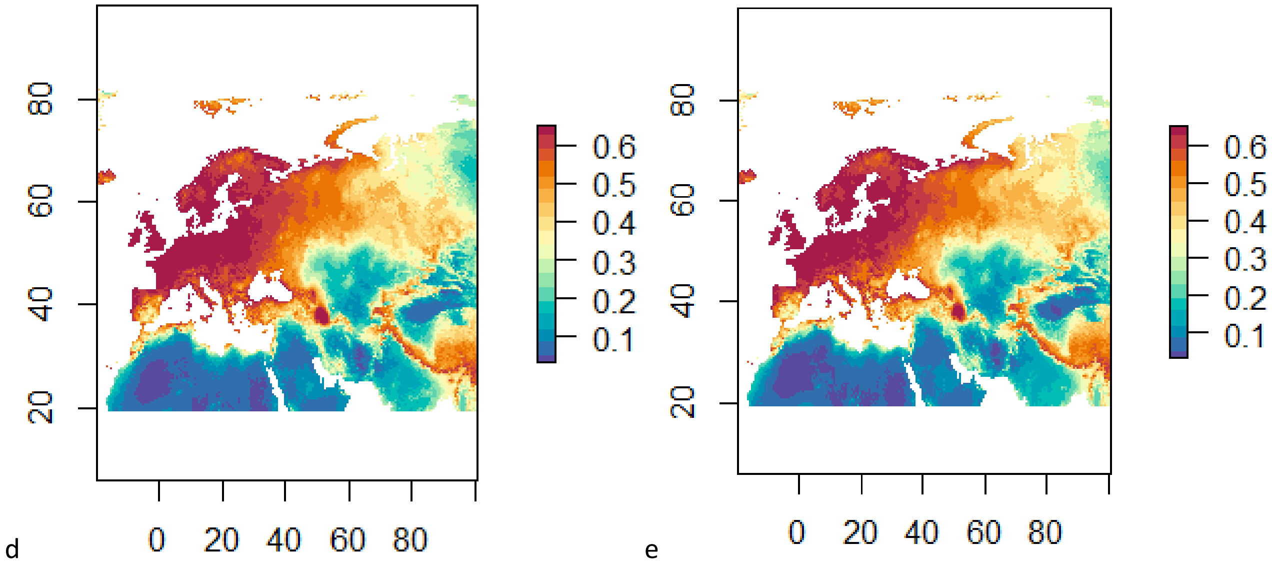


Figure 23d and 23e: Results of the simulation for summer 2061-80 (d) and 2081-2100 (e)

Novel points

From *Figure 24* it can be observed the territories where the largest amount of bioclimatic variables overlap are located in England and around the Baltic Sea, Finland, and west Russia. The rest of Europe is covered with very light blue shades, most of them tending to white colours. On the other hand, red areas correspond to arid and desertic territories, which are therefore predicted to become less and less suitable.

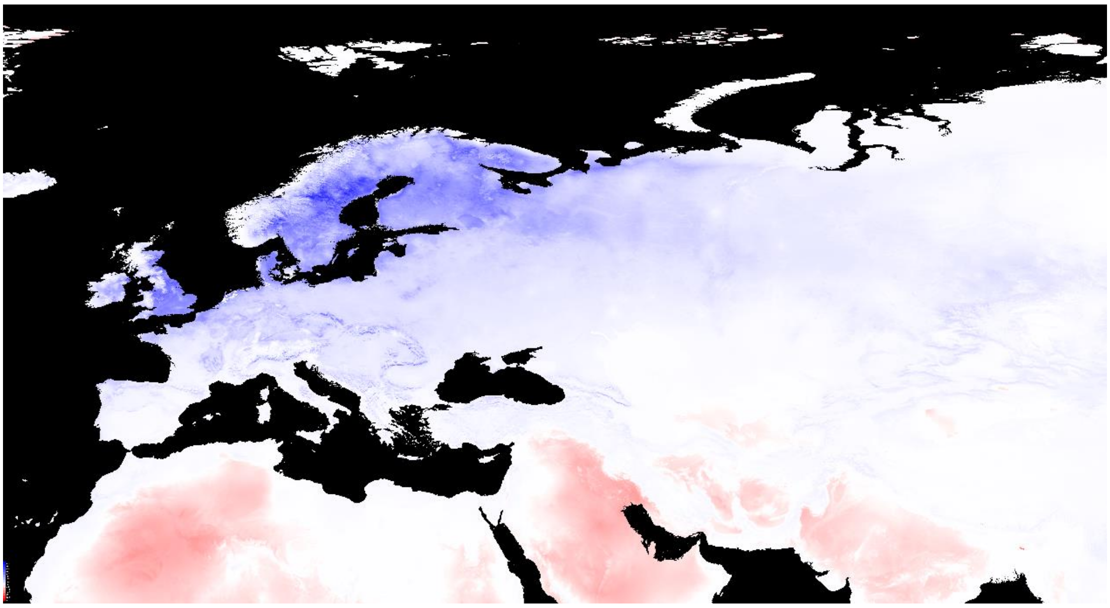


Figure 24: novel point in the hotlayers climate conditions: summer 2081-2100

Present and forecasted winter

Suitability maps

The Maxent model for the distribution in winter for the species *Anas platyrhynchos* resulted in an Area Under Curve (AUC) of 0.539, testifying a good predictive performance. From the previous figures (Fig. 25a-e) it can be observed a comparison among present summer and predicted future conditions for *Anas platyrhynchos* species. It can be seen an almost homogeneous coloured European continent, with shades varying from light green to yellow. The most evident change it can be noticed for Arctic Sea islands going onto further scenarios.

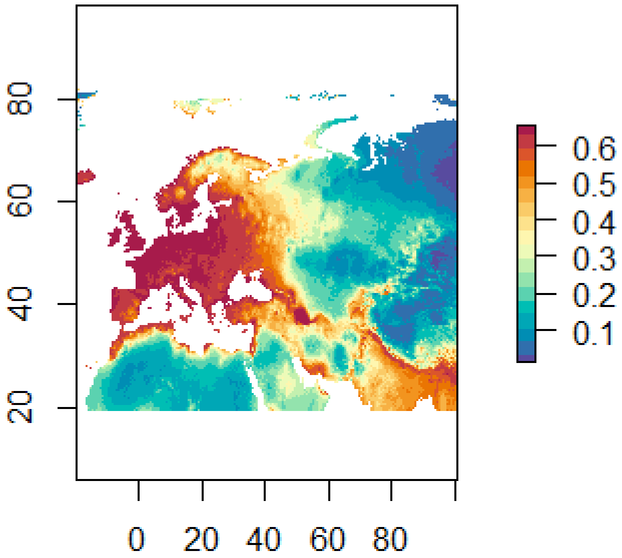


Figure 25a: representation of the Maxent model for present situation

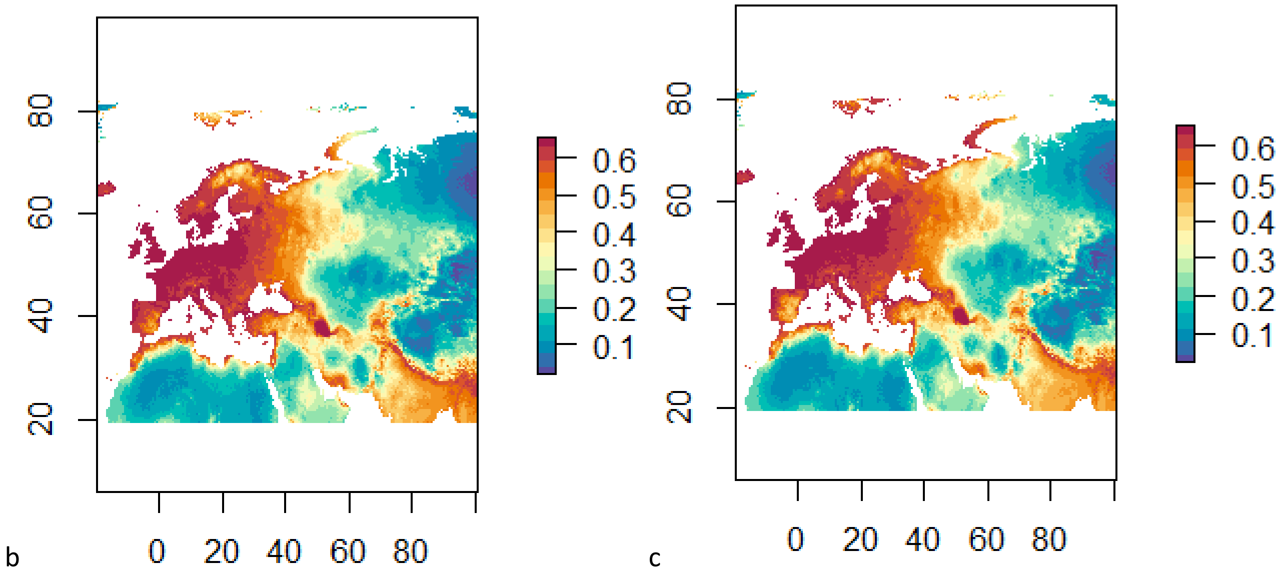


Figure 25b and 25c: Results of the simulation for winter 2021-40 (b) and 2041-60 (c)

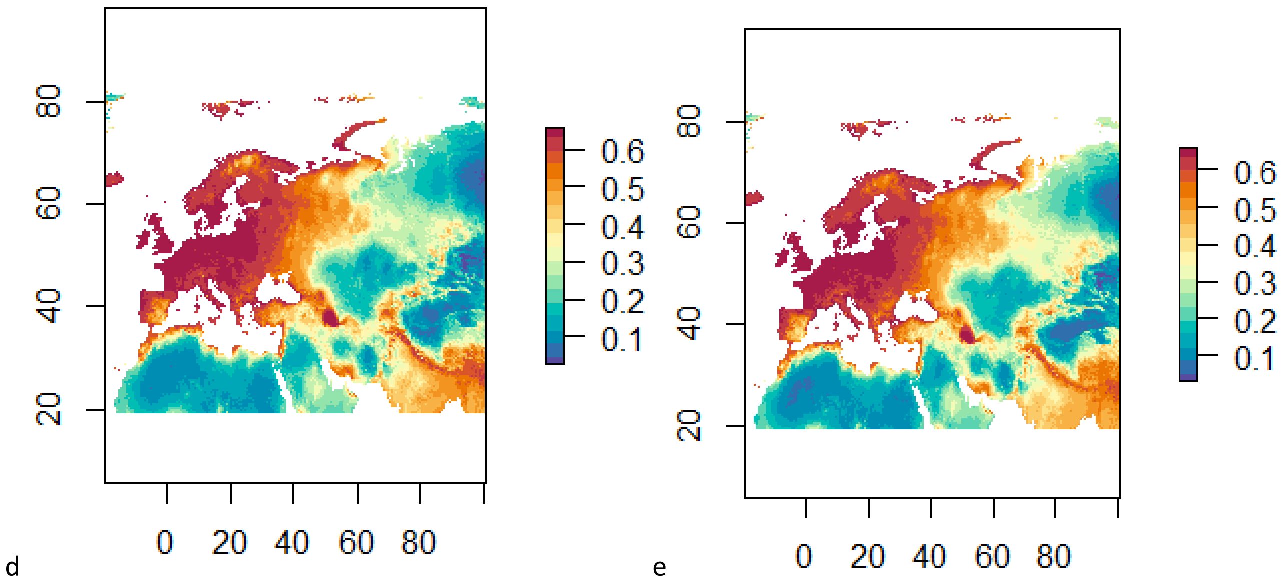


Figure 25d and 25e: Results of the simulation for winter 2061-80 (d) and 2081-2100 (e)

Novel points

As regards the novel point in the outlayers climate conditions (Fig. 26) it is observable from the above figure, high overlap of climatic variables in the regions over Poland, the Baltic republics and south of Sweden. Lighter shadows of blue cover the majority of the north-east of European countries while, red areas, correspond to arid and desertic habitat. An exception is, in this case too, the coastal region of India and Pakistan, painted in red but considered suitable according to the probability distribution map.

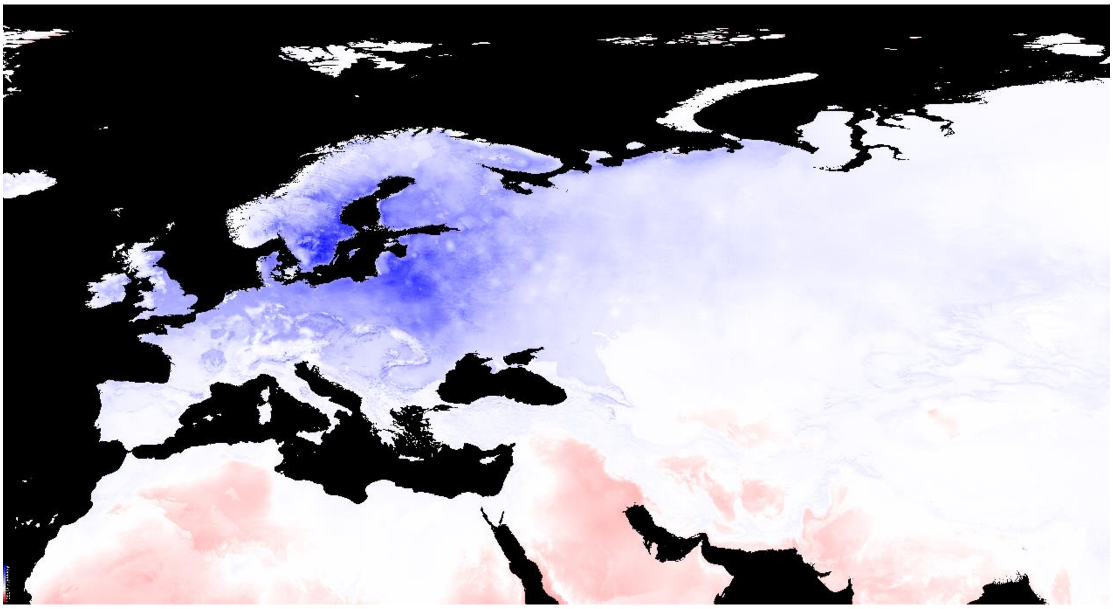


Figure 26: novel point in the hotlayers climate conditions: winter 2081-2100

Aythya ferina (Common pochard)

Present and forecasted summer

Suitability maps

The Maxent model for the distribution in summer for the species *Aythya ferina* resulted in an Area Under Curve (AUC) of 0.672, testifying a good predictive performance. In the following figures (Fig. 27 a-e) are compared present summer and predicted conditions for Aythya farina species. This species can be observed to be widely spread around the European continent; suitable conditions are indeed diffused homogeneously all around the continent and also beyond the borders with Russia. Moving toward further future scenarios, the coloured areas are not changing a lot, Arctic islands do not appear to become more suitable, with as only exception the southern part of Novaja Zemlja. On the other hand, light blue coloured surface over Russia becomes greener.

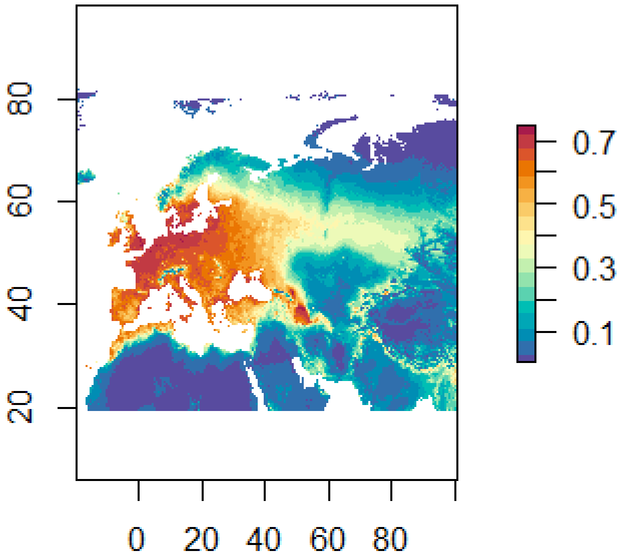
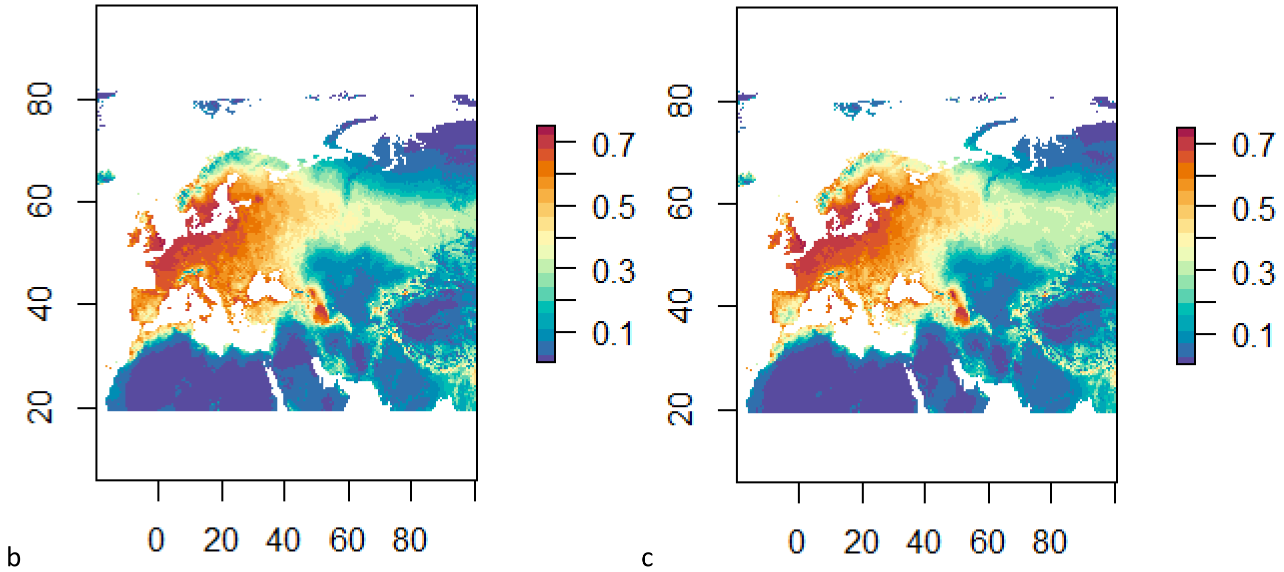


Figure 27a: representation of the Maxent model for present situation



b

c

Figure 27b and 27c: Results of the simulation for summer 2021-40 (b) and 2041-60 (c)

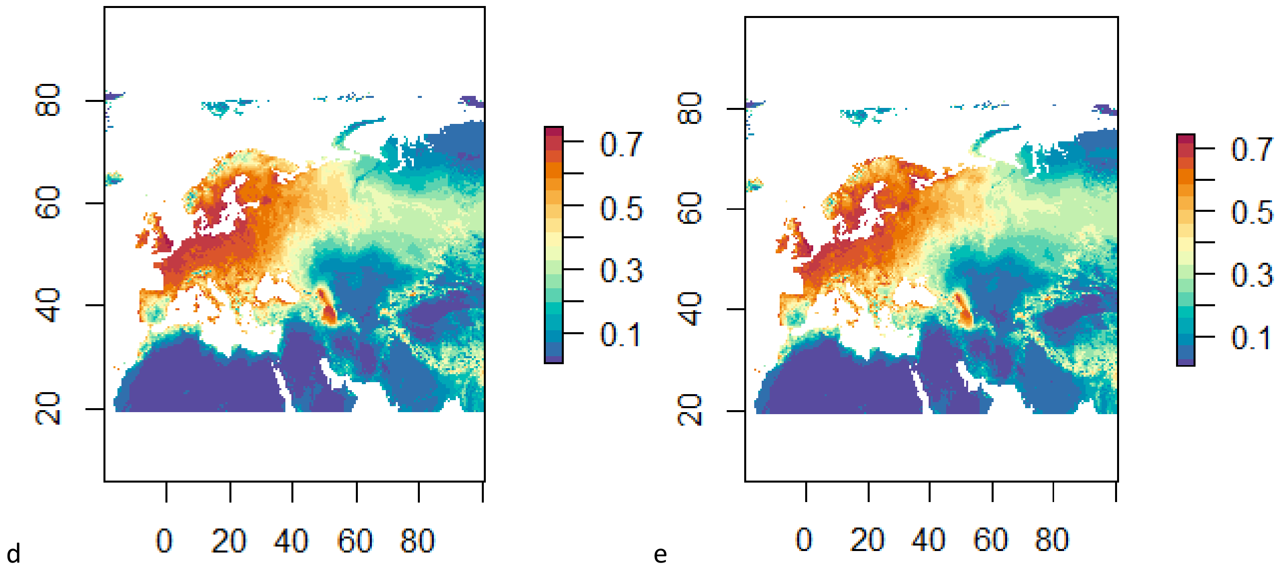


Figure 27d and 27e: Results of the simulation for summer 2061-80 (d) and 2081-2100 (e)

Novel points

What can be seen in the previous picture (Fig. 28) is an intense blue colour pattern in central and east Europe, in general along the Baltic Sea coastal areas and west-Russia territories. But some blue areas are also noticeable in the north of France, some places in Spain, and the Po valley. This pattern is consistent with the predicted suitability map. By contrast, the regions coloured in red correspond mainly to arid and desert habitats.

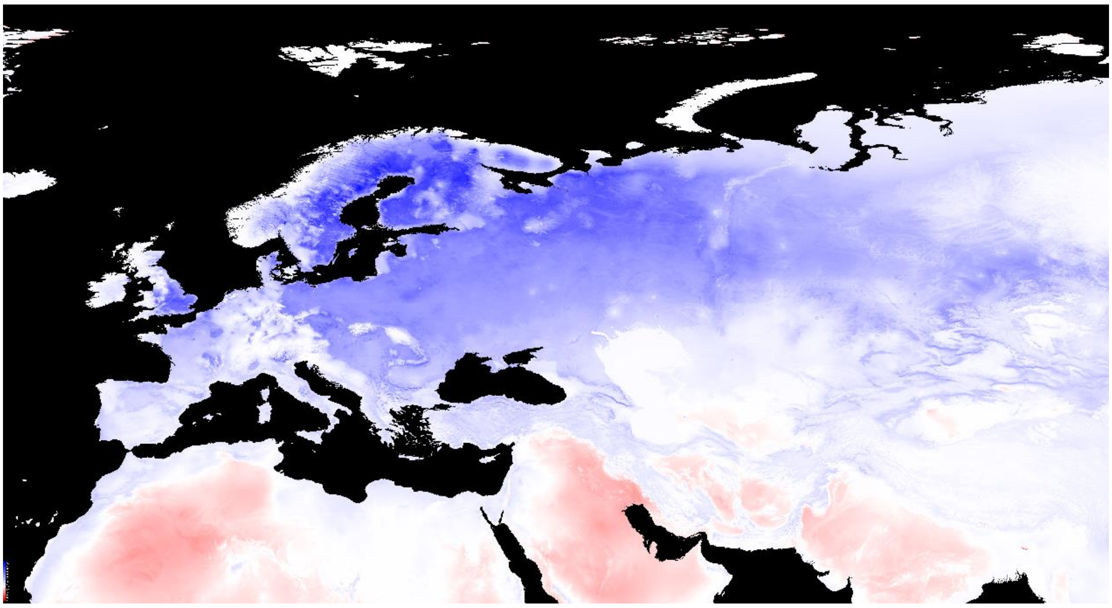


Figure 28: novel point in the hotlayers climate conditions: summer 2081-2100

Present and forecasted winter

Suitability maps

The Maxent model for the distribution in winter for the species *Aythya ferina* resulted in an Area Under Curve (AUC) of 0.648, testifying a good predictive performance. In present condition (Fig. 29a), the suitable territories for winter season are contained within European borders, and the Baltic peninsula is excluded almost completely. Moving onto toward further future scenarios (Fig. 44b-e), Scandinavia countries becomes more and more green and yellow. The same happens to Arctic islands and west territories of Russia. Regarding the areas within and near India, no noticeable changes seem to occur.

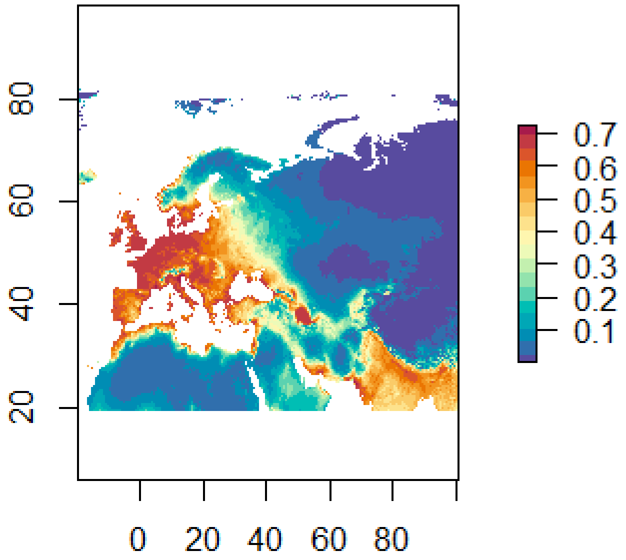


Figure 29a: representation of the Maxent model for present situation

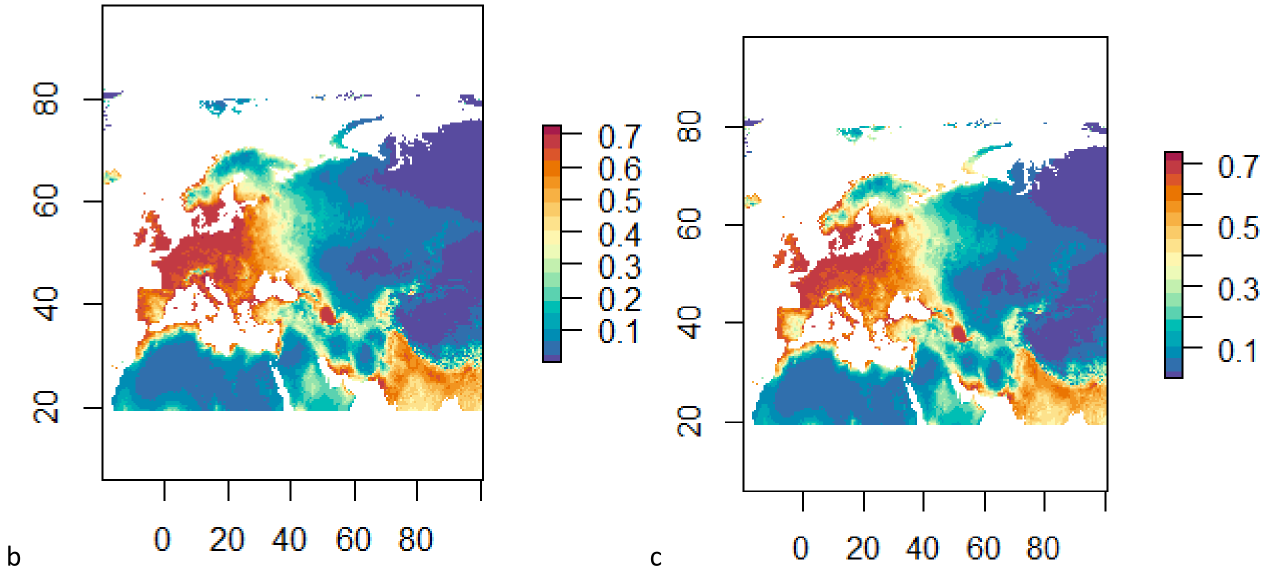


Figure 29b and 29c: Results of the simulation for winter 2021-40 (b) and 2041-60 (c)

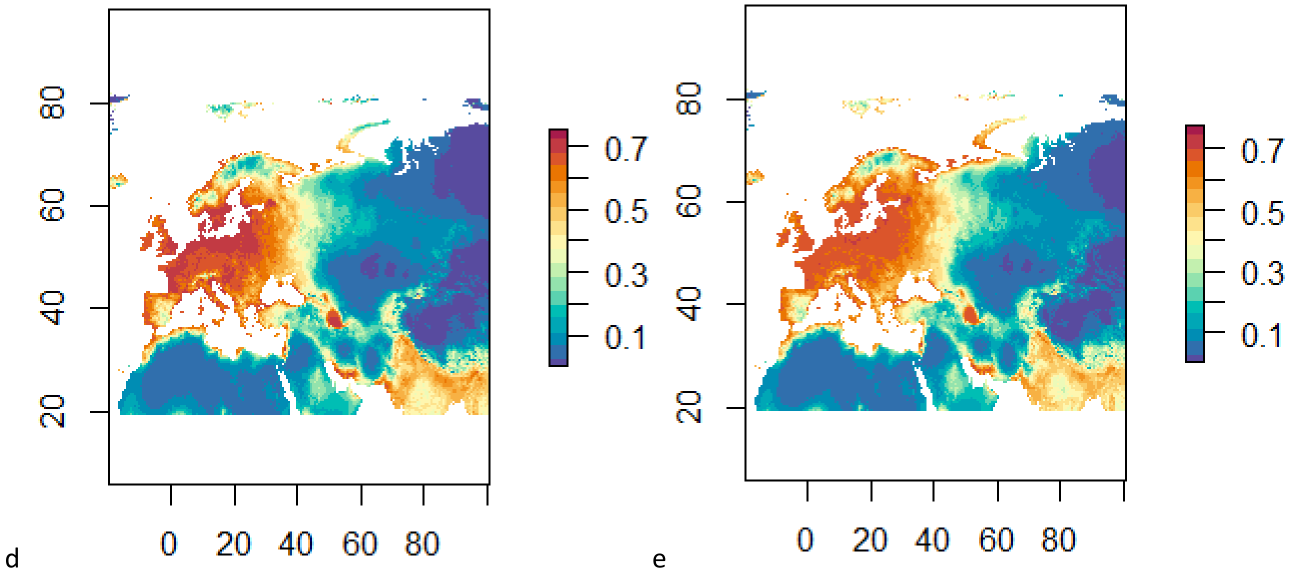


Figure 29d and 29e: Results of the simulation for winter 2061-80 (d) and 2081-2100 (e)

Novel points

Differently from the summer plot, the most intense blue coloured areas in *Figure 30* are located a bit southern, over Ukraine, Russia and the south of Finland. Moreover, other regions with a predicted high overlap of environmental and climatic variables corresponds to central-east European countries. This pattern is consistent with the predicted suitability map. Red coloured regions correspond to arid and desertic places, with the exception of India and Pakistan coastal areas.

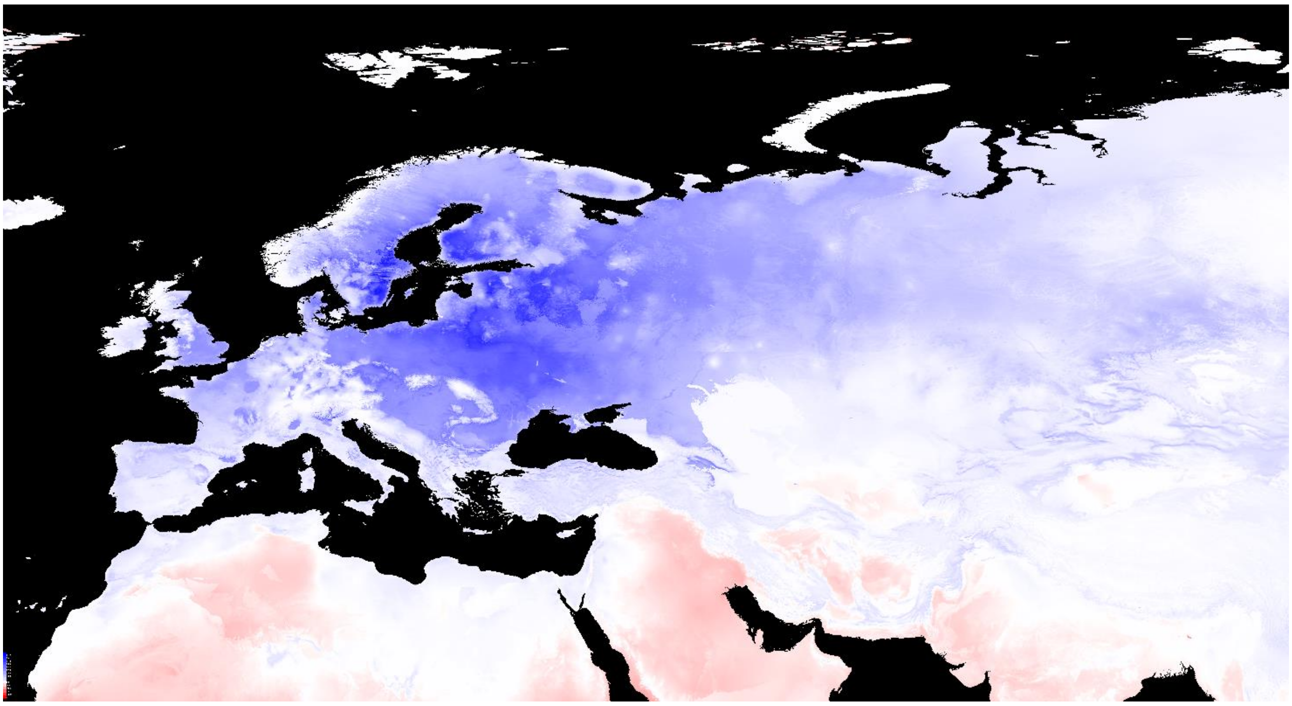


Figure 30: novel point in the hotlayers climate conditions: winter 2081-2100

Aythya fuligula (Tufted duck)

Present and forecasted summer

Suitability maps

The Maxent model for the distribution in summer for the species *Aythya fuligula* resulted in an Area Under Curve (AUC) of 0.599, testifying a good predictive performance. At current situation (Fig.31a) it can be observed the majority of the European continent is considered suitable, with homogeneous distribution of green-to-yellow colours. Only extreme southern territories are light blue painted, as south of Spain, Sicily Island, Greece, and Turkey. Moving onto the end of the century (Fig. 31b-e), it is observable a gradual shift toward northern latitudes. In particular, Arctic Ocean islands, Murmansk peninsula and Russian coastal areas are predicted to become more suitable. On the contrary, European regions at lower latitudes becomes bluer, as they seem to lose suitable conditions for this species. Among these countries, it can be seen this pattern in Spain, Greece, Turkey, and Italy.

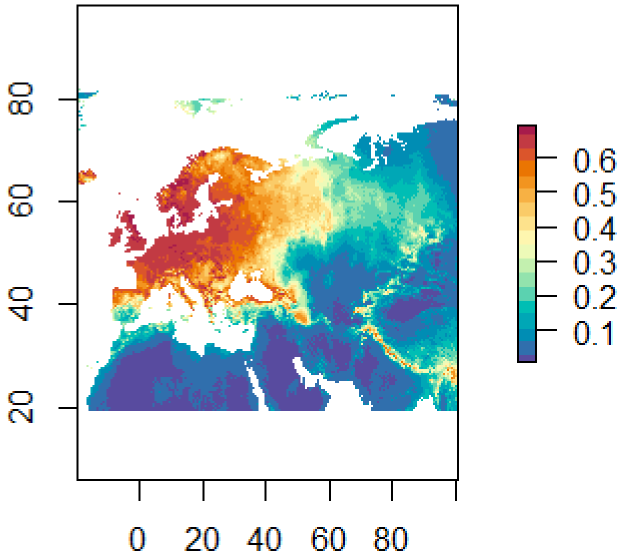


Figure 31a: representation of the Maxent model for present situation

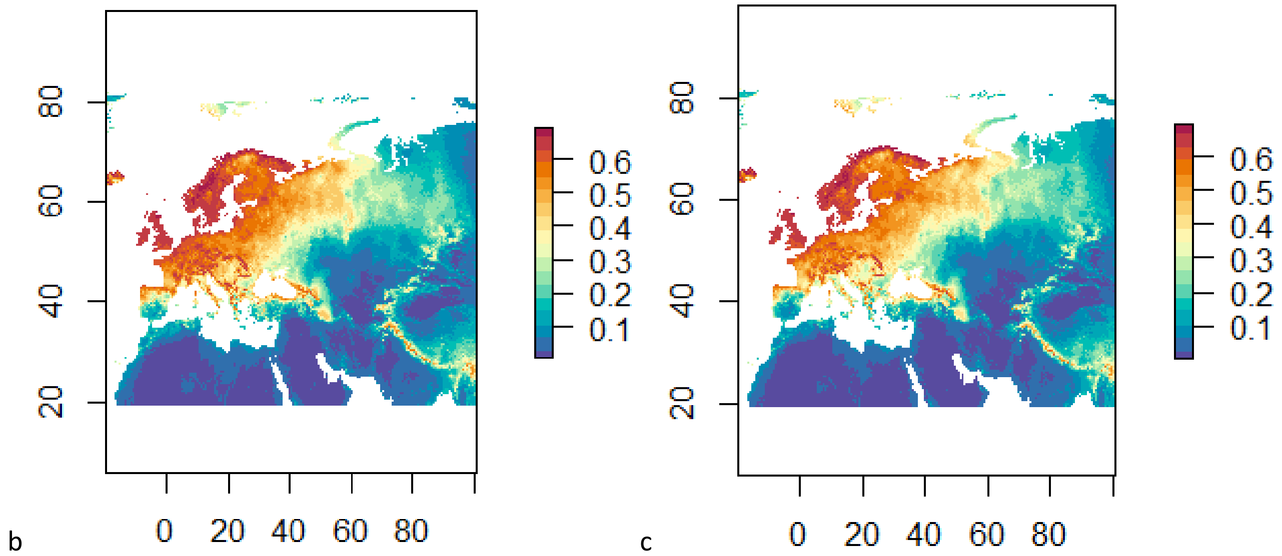


Figure 31b and 31c: Results of the simulation for summer 2021-40 (b) and 2041-60 (c)

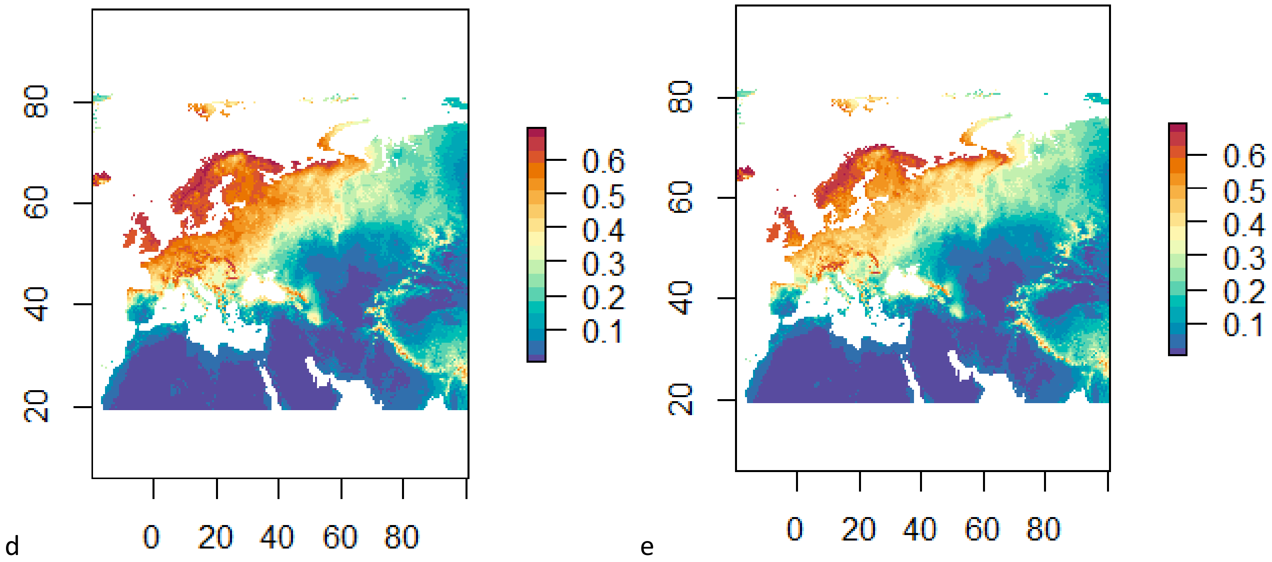


Figure 31d and 31e: Results of the simulation for summer 2061-80 (d) and 2081-2100 (e)

Novel points

From the following plot (Fig. 32) it is observable that the predicted areas in which there would be the highest overlay of all the variables parameters, making those regions particularly suitable, under a climatic and weather perspective, correspond to the northern region of Scandinavian peninsula. Light blue colour covers the most of European continent, mainly the eastern countries. On the other hand, red colour (novel points) is well determined over north Africa, Middle East, India, and Pakistan countries.

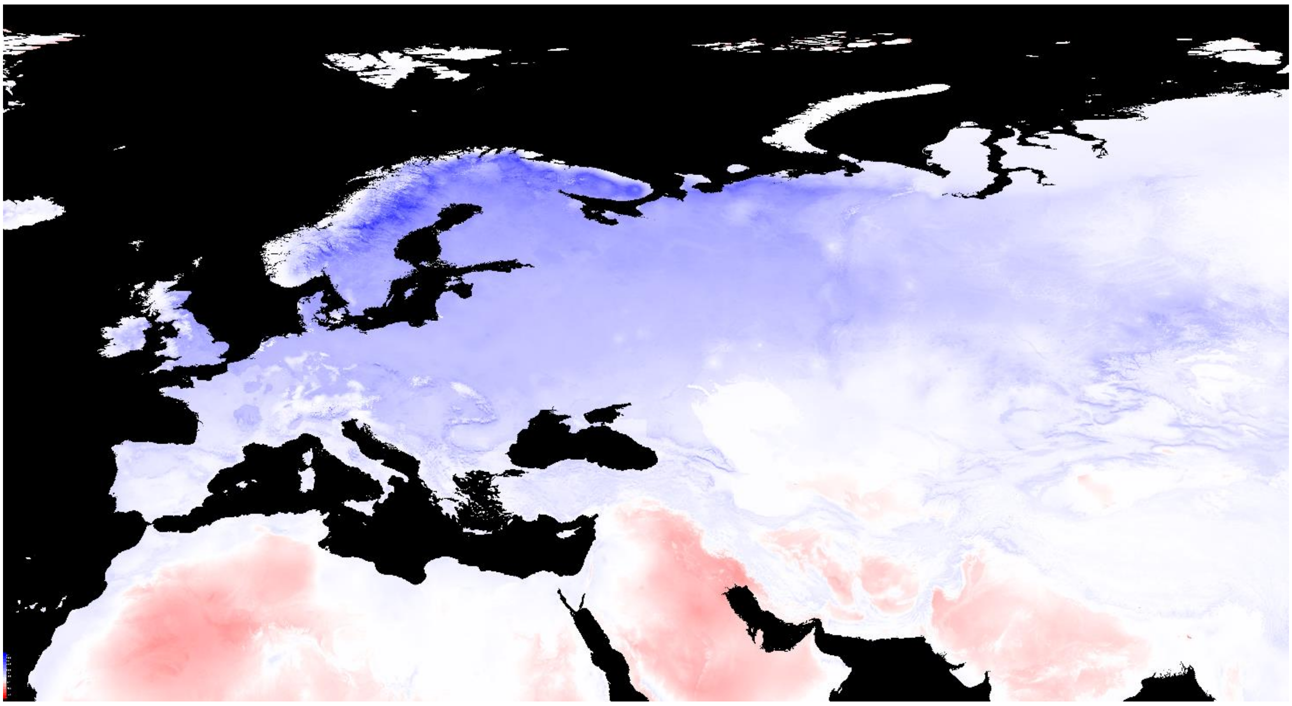


Figure 32: novel point in the hotlayers climate conditions: summer 2081-2100

Present and forecasted winter

Suitability maps

The Maxent model for the distribution in winter for the species *Aythya fuligula* resulted in an Area Under Curve (AUC) of 0.605, testifying a good predictive performance. In *Figure 33a* it can be observed the present suitability conditions for winter season. Compared to summer season, modelled more suitable regions are placed at southern latitudes. It can be seen a big blue area over the north of Scandinavia countries. India is given as a suitable country too. Moving onto further scenarios (33b-e), green and yellow areas seem to expand toward northern latitudes, reaching all the territories of Scandinavian peninsula, west coasts of Russia, and the Arctic Ocean islands. Dinally, also Russian flatlands above Ukraine are predicted to become more suitable.

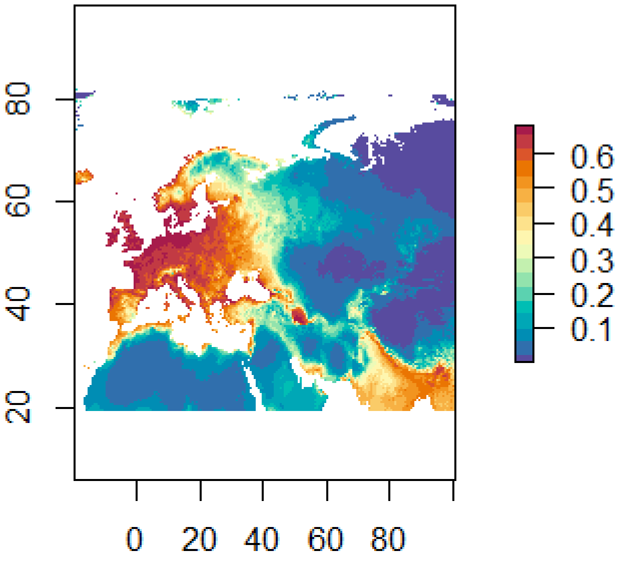


Figure 33a: representation of the Maxent model for present situation

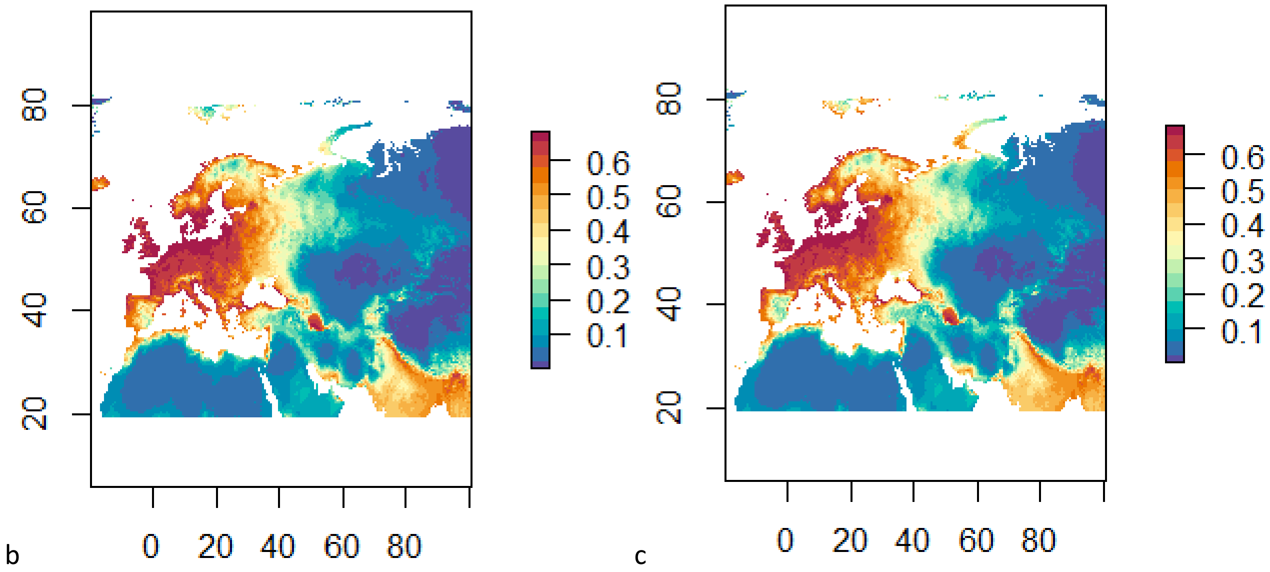


Figure 33b and 33c: Results of the simulation for winter 2021-40 (b) and 2041-60 (c)

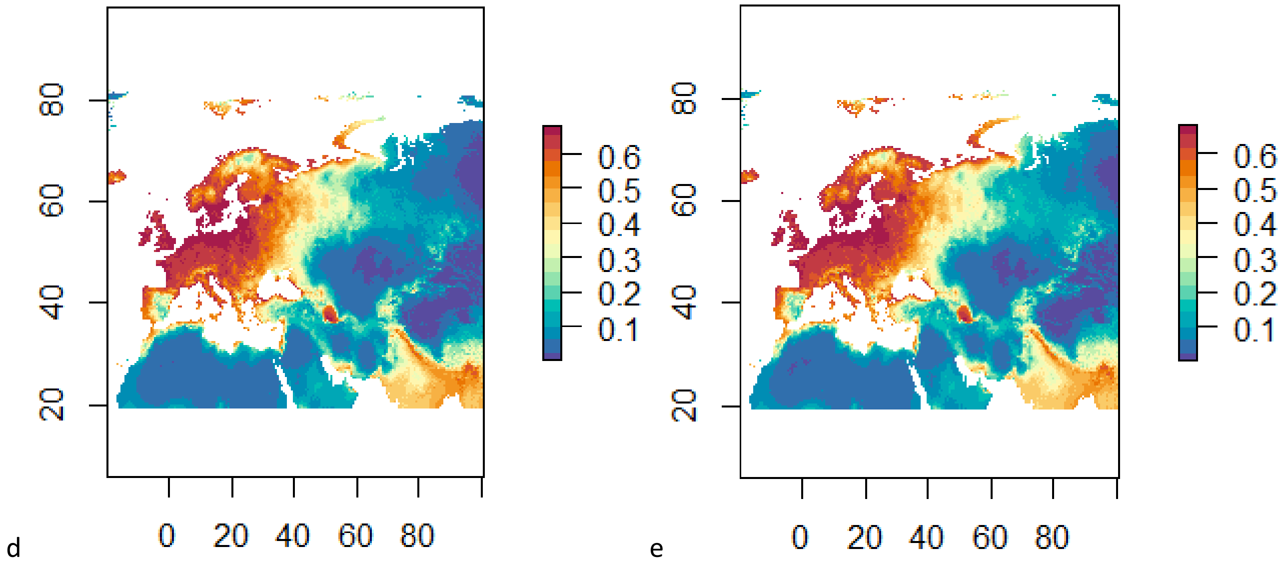


Figure 33d and 33e: Results of the simulation for winter 2061-80 (d) and 2081-2100 (e)

Novel points

Looking at Figure *34*, the areas in which it is predicted to happen the highest overlay of environmental and bioclimatic variables, for the end of the century, they are located all around Baltic Sea borders. Therefore, a bit southern compared to the summer plot. The novel points, corresponding to red areas, cover the regions of arid and desertic habitats, Iran, Pakistan, and India coastal areas.

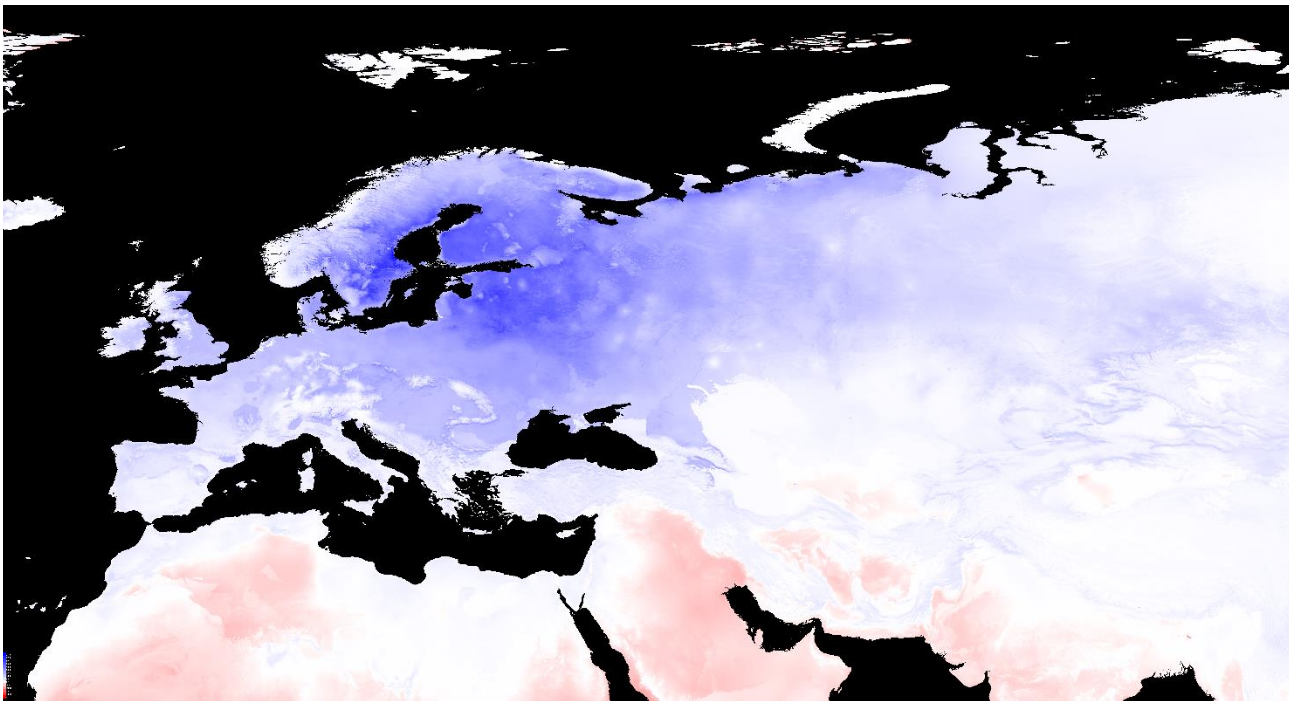


Figure 34: novel point in the hotlayers climate conditions: winter 2081-2100

Mareca penelope (Eurasian Wigeon)

Present and forecasted summer

Suitability maps

The Maxent model for the distribution in summer for the species *Mareca penelope* resulted in an Area Under Curve (AUC) of 0.868, testifying a good predictive performance. That the model performs very well it can be understood looking at the suitability plots (Fig. 35 a-e). For present condition (Fig. 56a), orange to red coloured areas are observed around Baltic Sea, some regions in France and in the South of England. Regions in the southern European countries, as Italy and Spain, are painted with light green colours, while all around Europe a good suitability is expected. Moving toward the end of the century, red areas around Baltic Sea are expected to expand their borders toward higher latitudes, moving along Finland, the Murmansk peninsula, finally reaching northern coasts of Russia. Svalbard islands are slightly interested in becoming a more suitable region, while the southern part of Novaja Zemlja is expected to increase a lot its favourable climatic conditions. As last consideration, it seems that countries like Spain, Italy, Greece, and Turkey are expected to lose favourable conditions.

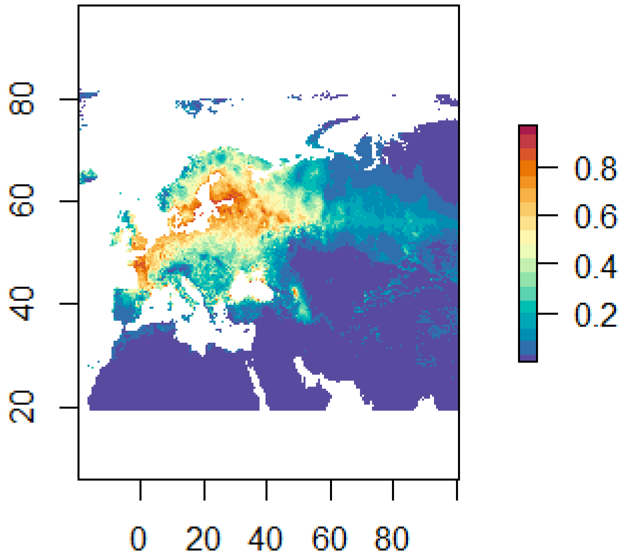


Figure 35a: representation of the Maxent model for present situation

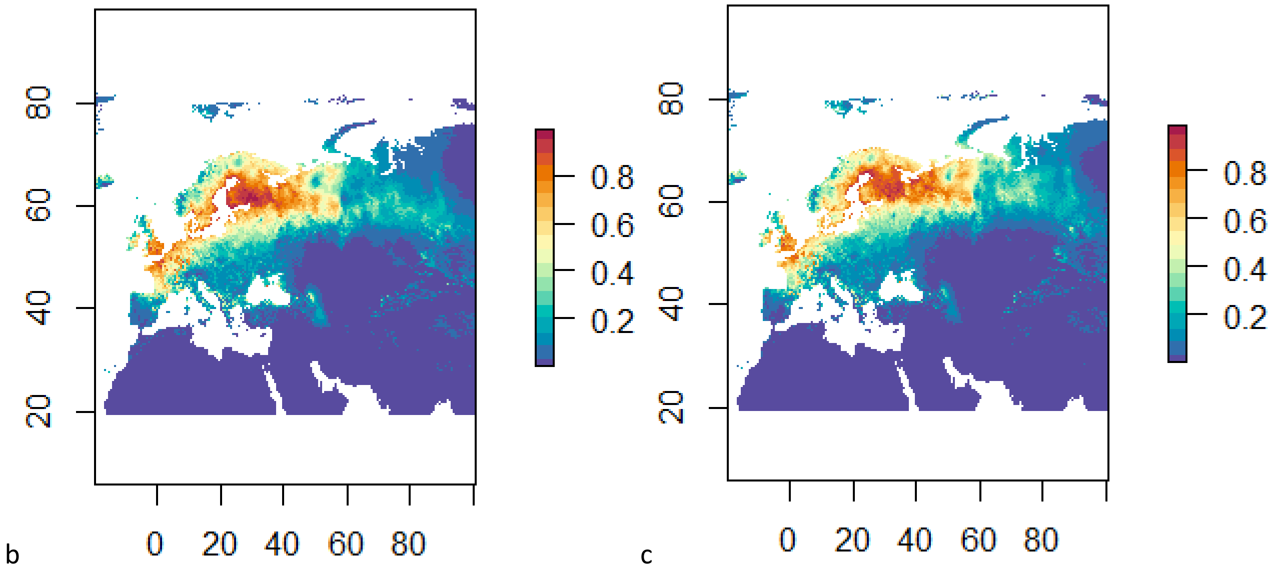


Figure 35b and 35c: Results of the simulation for summer 2021-40 (b) and 2041-60 (c)

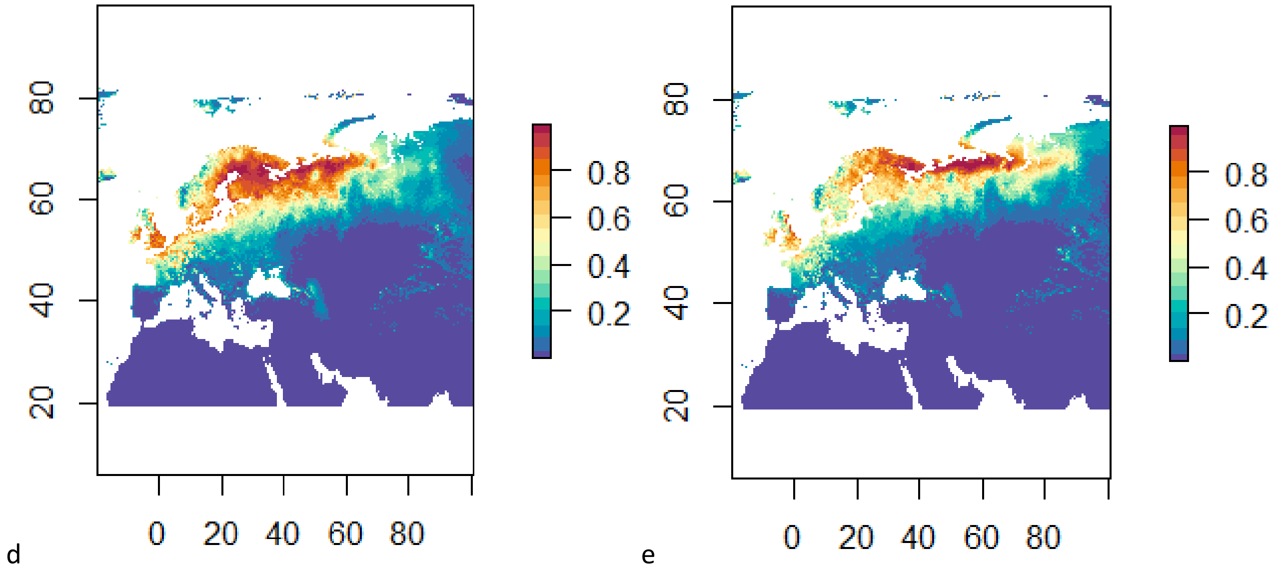


Figure 35d and 35e: Results of the simulation for summer 2061-80 (d) and 2081-2100 (e)

Novel points

Areas with the highest overlay conditions, for environmental and bioclimatic variables, are predicted to occur mostly above Russian flatlands, eastern Europe and the norther part of Scandinavian peninsula. Red areas correspond to arid and desertic habitat regions, and with Himalayas (Fig. 36).

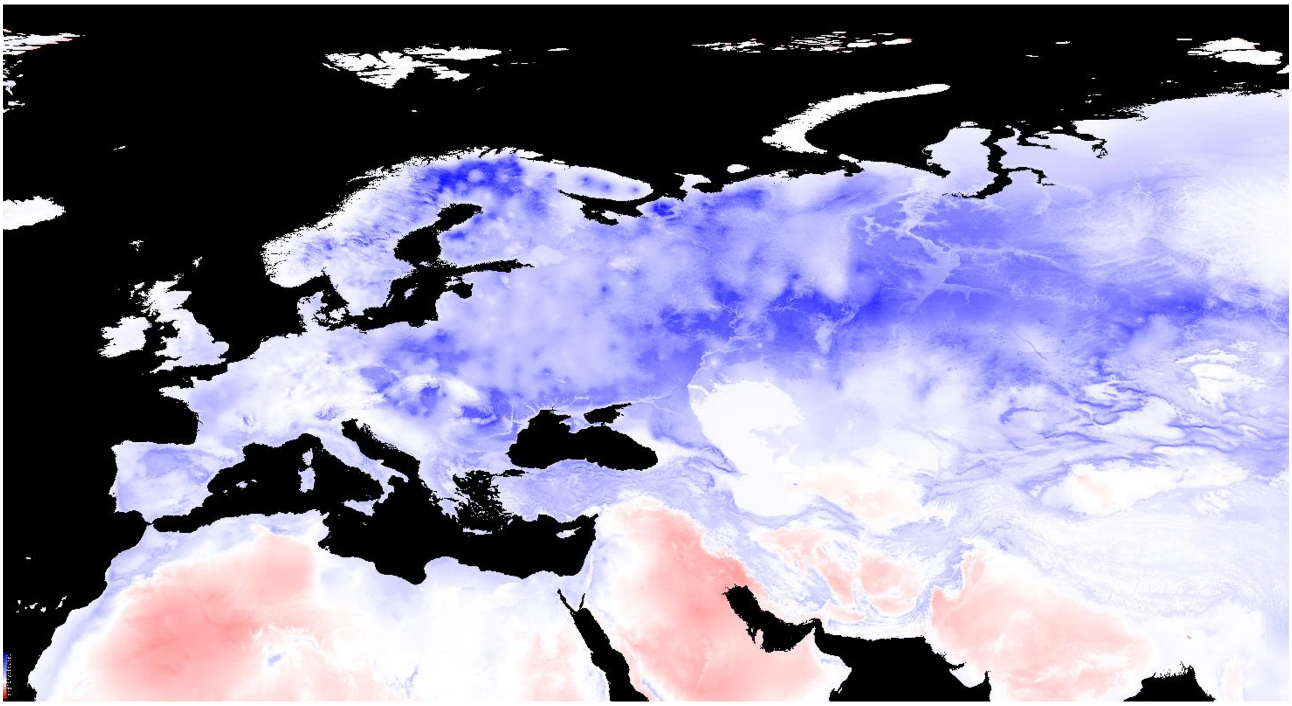


Figure 36: novel point in the hotlayers climate conditions: summer 2081-2100

Present and forecasted winter

Suitability maps

The Maxent model for the distribution in winter for the species *Mareca penelope* resulted in an Area Under Curve (AUC) of 0.838, testifying a good predictive performance. From the suitability map of present situation (Fig. 37a) there can be observed some orange patches in the Netherlands, England and Italy. The areas where the data was taken, and the test locations are distributed mainly within France, Belgium, and the Baltic Republics borders. Scrolling through the scenarios (Fig. 37b-e), red areas are increasing in their extension, expanding over Germany and Denmark, Sweden and Italy.

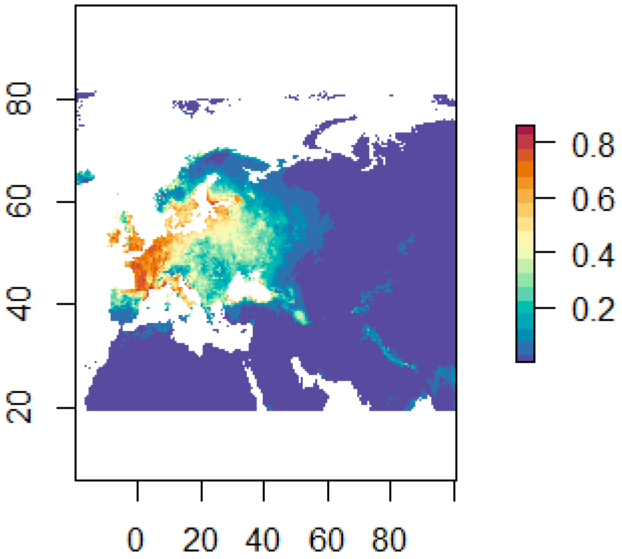


Figure 37a: representation of the Maxent model for present situation

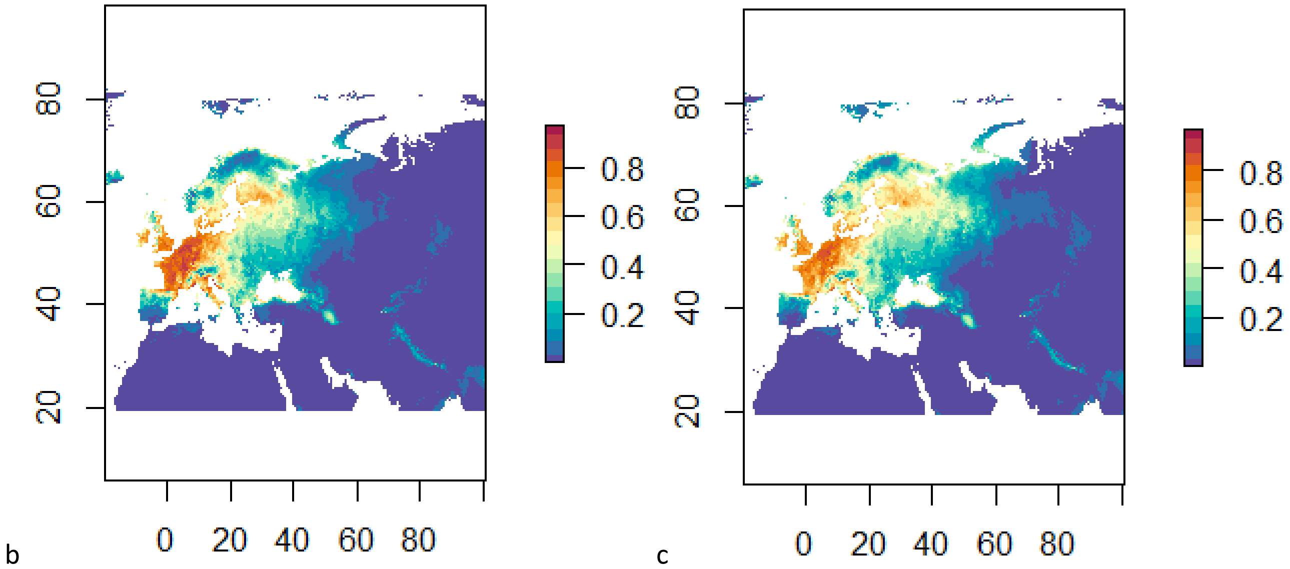


Figure 37b and 37c: Results of the simulation for winter 2021-40 (b) and 2041-60 (c)

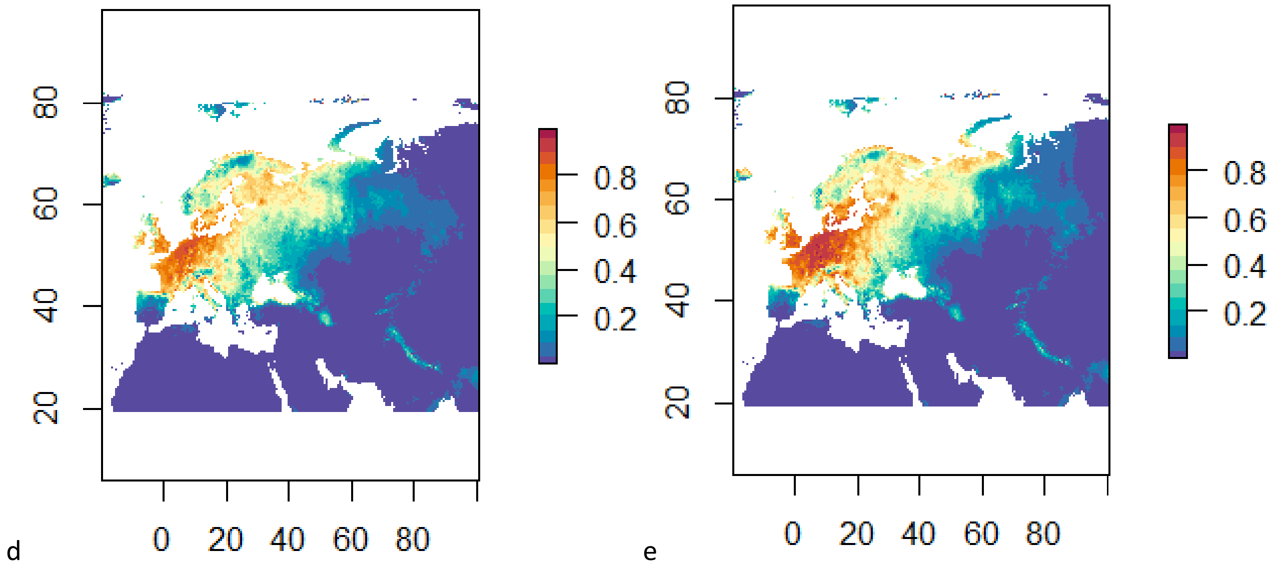


Figure 37d and 37e: Results of the simulation for winter 2061-80 (d) and 2081-2100 (e)

Novel points

From the previous picture (Fig. 38), it is observed that, by the end of the century, the predicted areas in which the highest number of climatological and environmental variables overlap seem to be central-east Europe, Scandinavian peninsula and the Po valley. Whilst red areas correspond to arid and desertic habitats, in addition to India and Pakistan coasts.

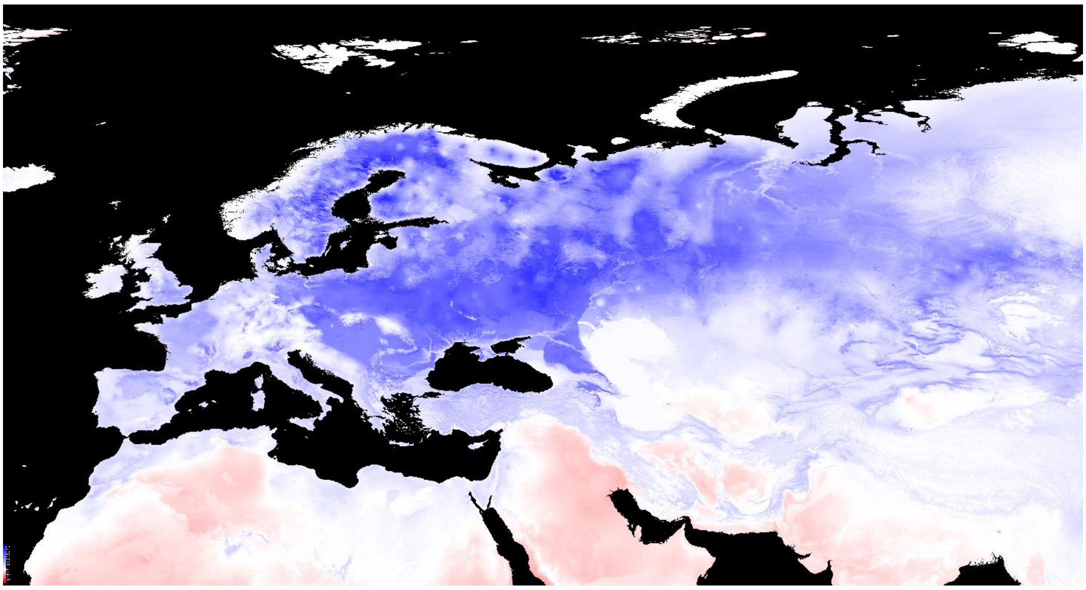


Figure 38: novel point in the hotlayers climate conditions: winter 2081-2100

Mareca strepera (Gadwall)

Present and forecasted summer

Suitability maps

The Maxent model for the distribution in summer for the species *Mareca strepera* resulted in an Area Under Curve (AUC) of 0.867, testifying a good predictive performance. From the previous figure (Fig. 39a) of the present suitability map situation, it can be seen that occurrences have been taken and tested almost within France and Baltic Republics. There is a quietly homogeneous pattern all around Europe with some patches with elevate probability in the Netherlands, Denmark, and Sweden. Moving toward further future scenarios (Fig. 39b-e), it can be observed that regions with high probability constantly shift toward northern latitudes. By the end of the century, red areas are predicted to reach the Murmansk peninsula, the southern part of Novaja Zemlja and a wide coastal area of Russia country. Moreover, green coloured areas are spread all over the northern part of Europe and Russia.

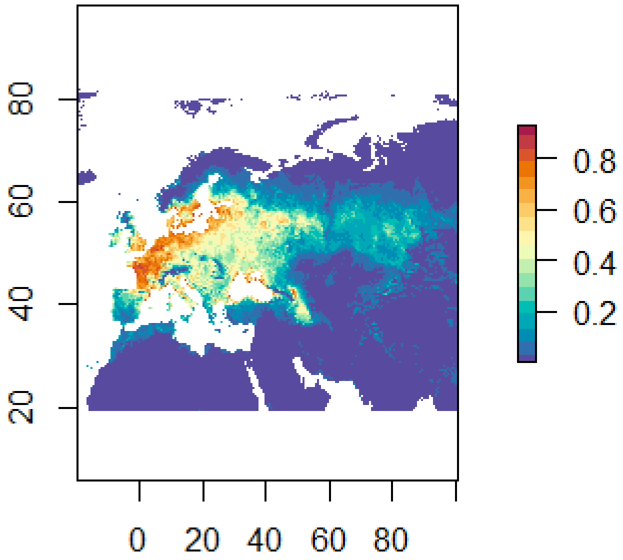


Figure 39a: representation of the Maxent model for present situation

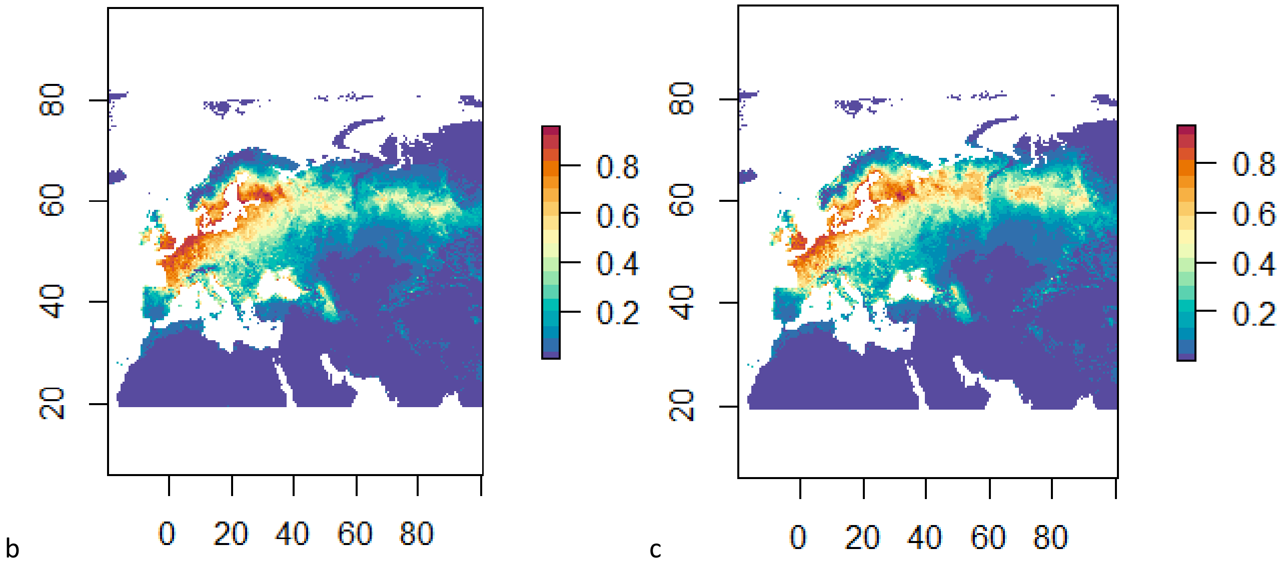


Figure 39b and 39c: Results of the simulation for summer 2021-40 (b) and 2041-60 (c)

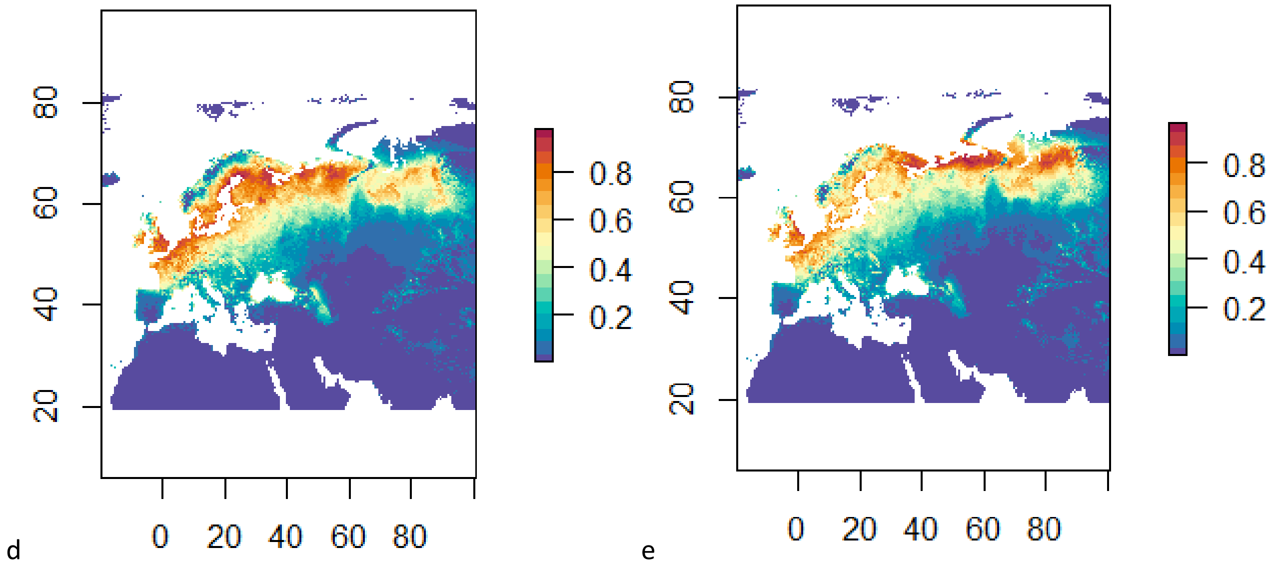


Figure 39d and 39e: Results of the simulation for summer 2061-80 (d) and 2081-2100 (e)

Novel points

Dark blue areas by the end of the century (Fig. 40) are predicted to follow the pattern of localities for suitability maps output. A huge part of Russia, Scandinavia and central Europe are among the most suitable, under a climatic and weather perspective given the high amount of considered variables which are overlapping. Red areas correspond mostly to arid and desertic habitat, and they don't touch territories where suitability maps predicted high probability to find good conditions, according to the parameters giving the fitness of *Mareca strepera*.

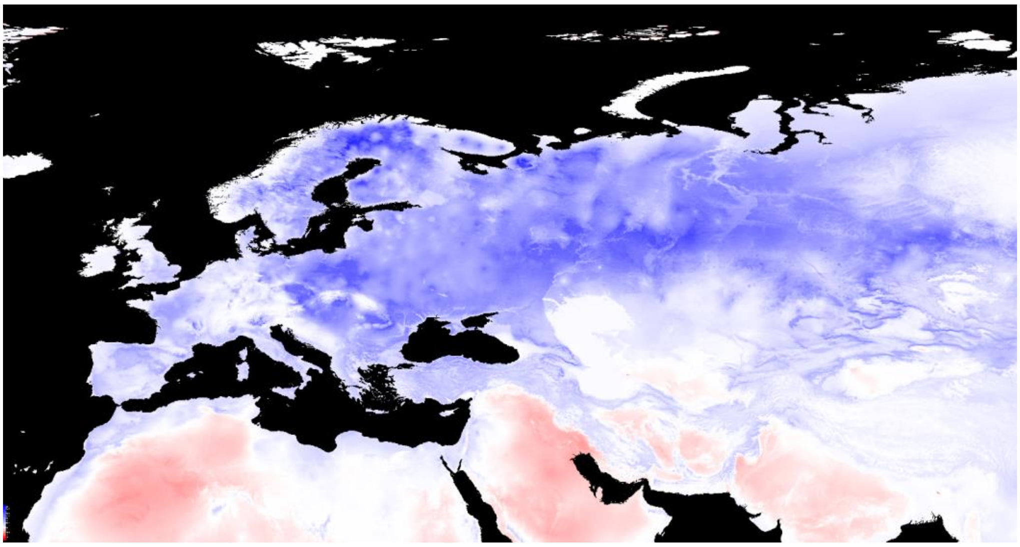


Figure 40: novel point in the hotlayers climate conditions: summer 2081-2100

Present and forecasted winter

Suitability maps

The Maxent model for the distribution in winter for the species *Mareca strepera* resulted in an Area Under Curve (AUC) of 0.843, testifying a good predictive performance. In *Figure 41a* it is shown the probability distribution of the suitable areas for the present. Suitable areas are quite located onto the European continental countries. Warm colours patches can be seen in the Netherlands and Italy, corresponding to the region of Venice lagoon. In the following pictures (Fig. 41b-e), of further predicted scenarios, localities with high probability to acquire suitable conditions are spreading mostly over Belgium, Germany, and other central European countries. Po Valley seems to keep a high probability to still present suitable conditions. It is predicted to become more suitable also the Scandinavian peninsula. Moreover, a small portion of Arctic Ocean islands change their colour from null to medium-low probability. In general, the predicted suitable area is mostly contained within European borders.

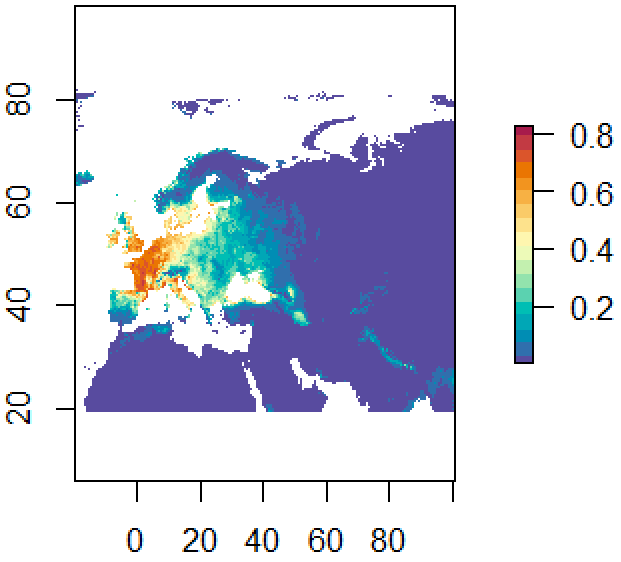


Figure 41a: representation of the Maxent model for present situation

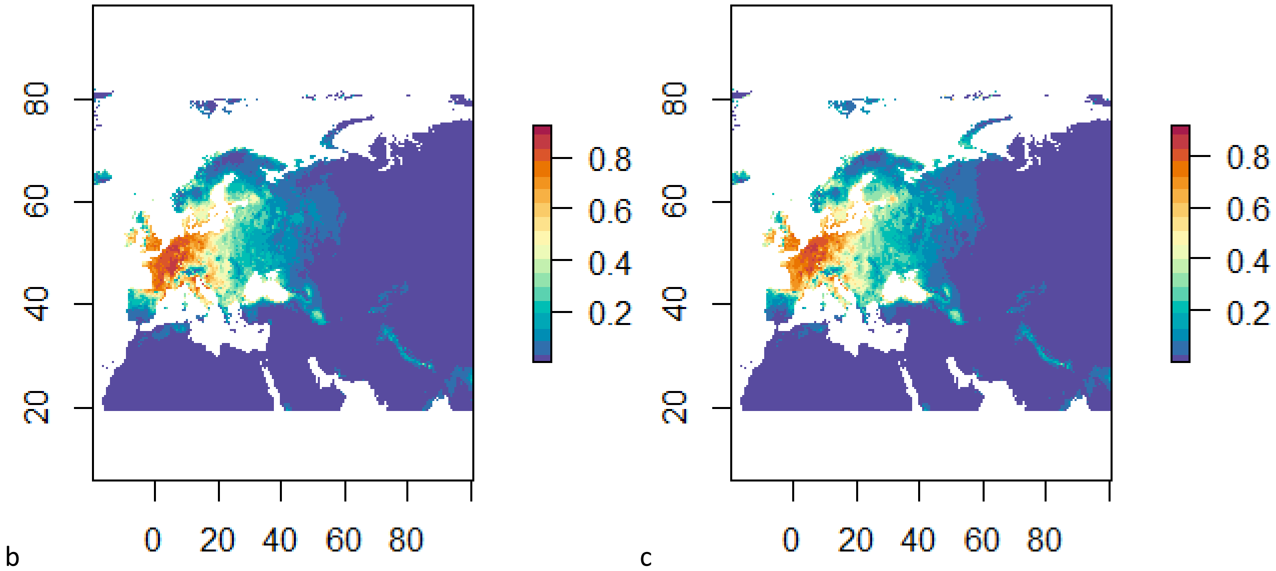


Figure 41b and 41c: Results of the simulation for winter 2021-40 (b) and 2041-60 (c)

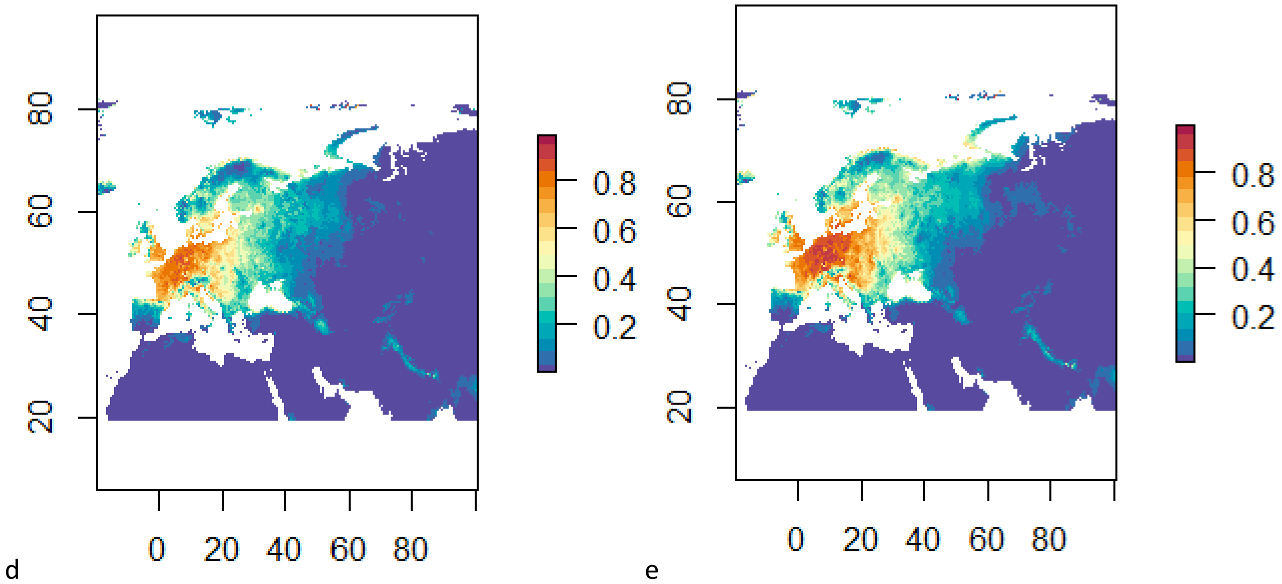


Figure 41d and 41e: Results of the simulation for winter 2061-80 (d) and 2081-2100 (e)

Novel points

According to the following picture (Fig. 42), regions with the higher number of variables which overlap themselves are predicted to be localised among Germany, Ukraine, and Finland. Intense blue colour can be noticed also over the Po valley. Novel points appear over desertic and arid areas.

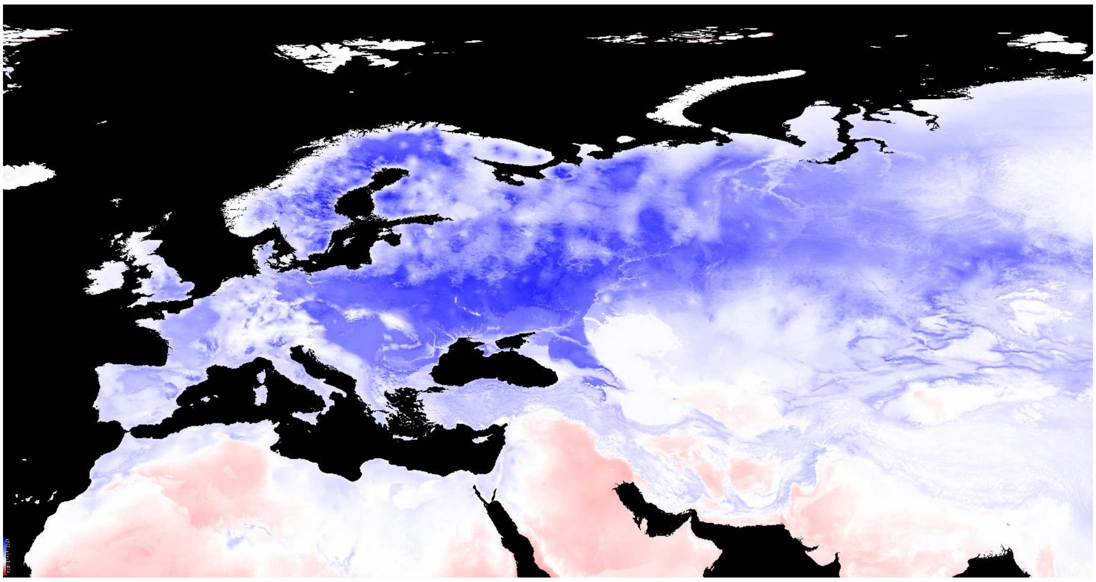


Figure 42: novel point in the hotlayers climate conditions: winter 2081-2100

Spatula clypeata (Northern shoveler)

Present and forecasted summer

Suitability maps

The Maxent model for the distribution in summer for the species *Spatula clypeata* resulted in an Area Under Curve (AUC) of 0.845, testifying a good predictive performance. In suitability maps figure (Fig. 43a), for the present condition, it can be seen a high probability distribution over the Netherlands, Denmark, and Sweden. There are also some patches in Italy and along Black Sea and Caspian Sea coasts. Moving onto the following predicted future scenarios (Fig. 43b-e), extremely high probability conditions are spread over England and central Europe. On the other hand, by the end of the century, it is predicted that those territories wouldn't have the same high probability as before, and that the areas with the highest suitable conditions would be located at higher latitudes, in Murmansk peninsula and Russian coasts along the Arctic Sea.

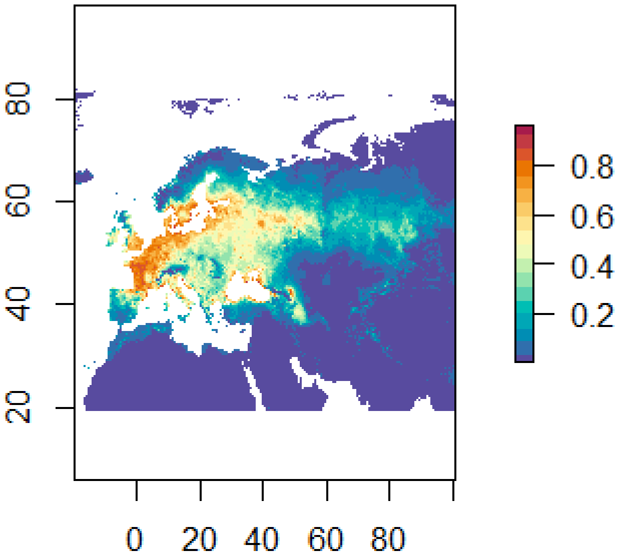
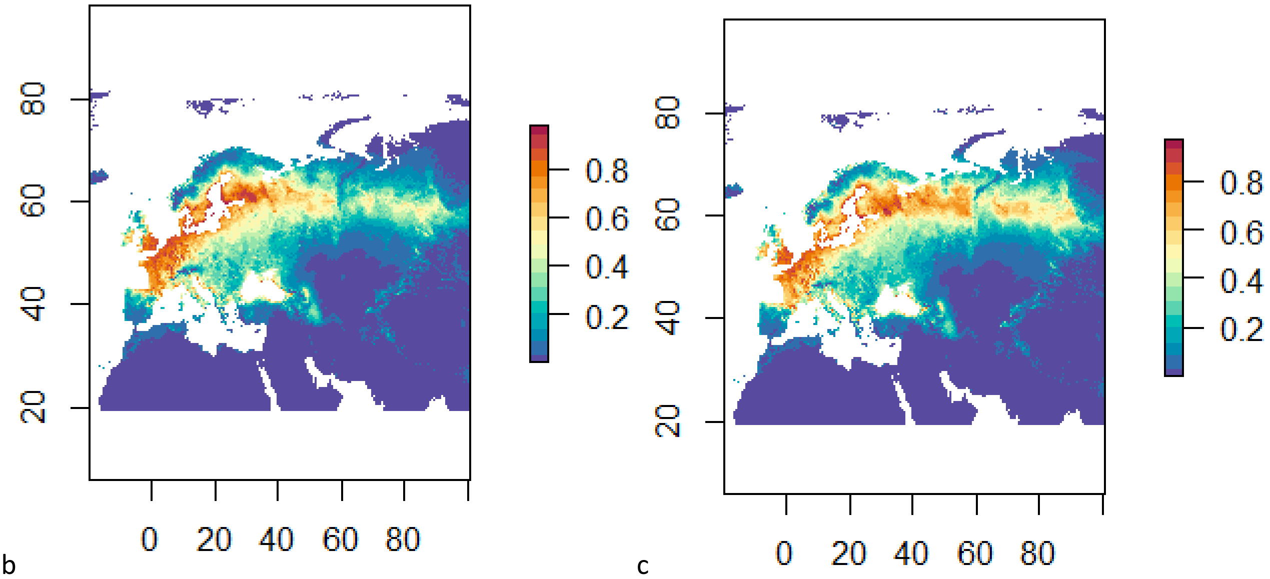


Figure 43a: representation of the Maxent model for present situation



b

c

Figure 43b and 43c: Results of the simulation for summer 2021-40 (b) and 2041-60 (c)

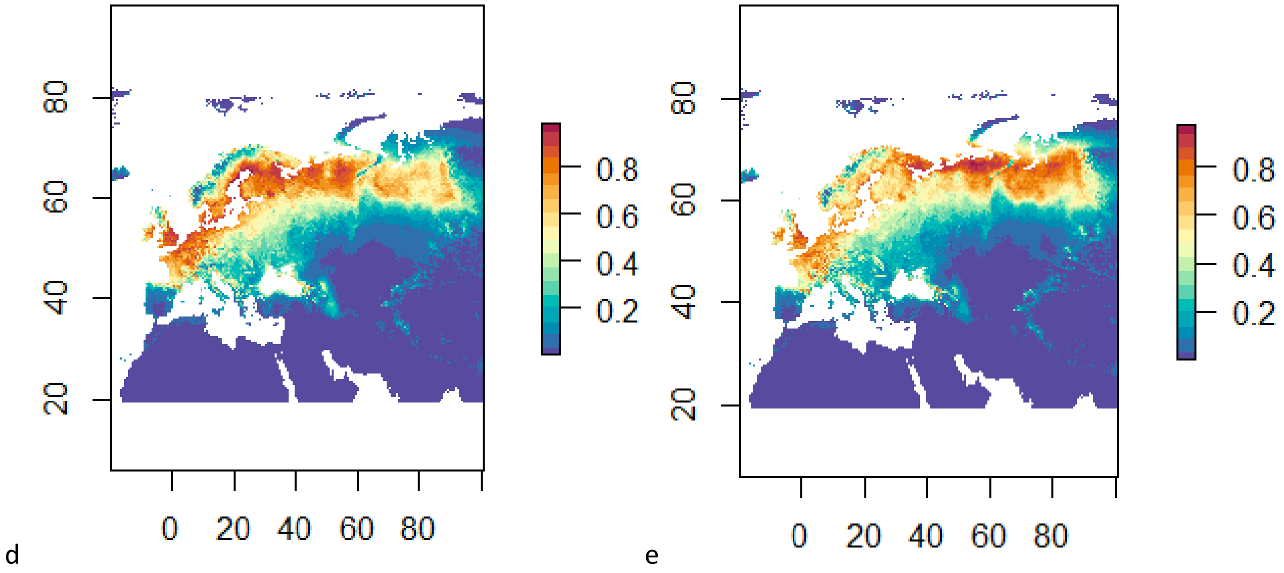


Figure 43d and 43e: Results of the simulation for summer 2061-80 and 2081-2100

Novel points

From the following plot (Fig. 44) it is observed the distribution of the predicted variables. The dark blue regions (areas in which there is the higher overlap of the environmental variables taken into account, and, therefore, the most suitable predicted climatological condition for *Spatula clypeata* species) characterise countries as Poland, Ukraine, Russia, Sweden, and Finland.

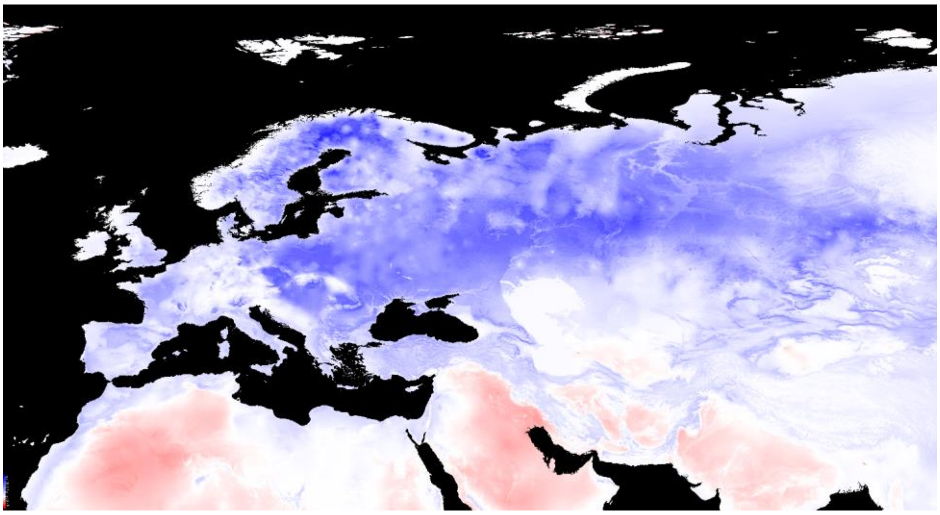


Figure 44: novel point in the hotlayers climate conditions: summer 2081-2100

Present and forecasted winter

Suitability maps

The Maxent model for the distribution in winter for the species *Anas acuta* resulted in an Area Under Curve (AUC) of 0.846, testifying a good predictive performance. According to the present suitability map (Fig. 45a), suitable conditions are concentrated among France, England, the Netherlands and few spots in Italy (Venice lagoon in particular). Moving on toward farther scenarios (Fig. 45b-e), high probability patches become wider and wider, mainly across England, France, and Germany countries. The Venice lagoon seems to keep its suitable characteristics across the century. Apart from very light blue regions at high latitudes, no relevant probability is returned outside European boundaries.

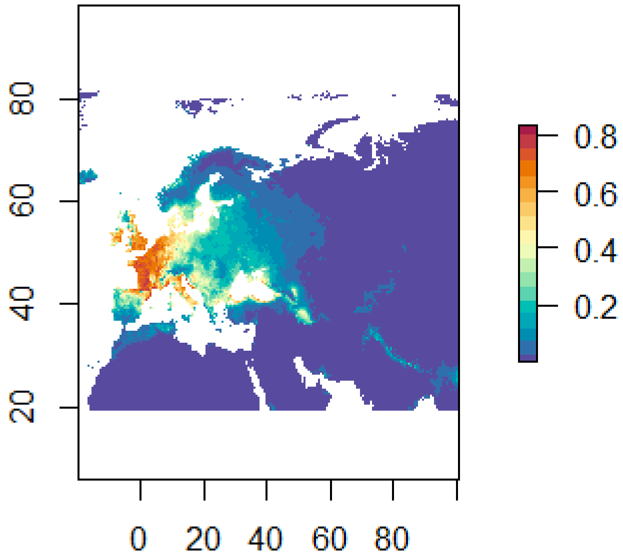


Figure 45a: representation of the Maxent model for present situation

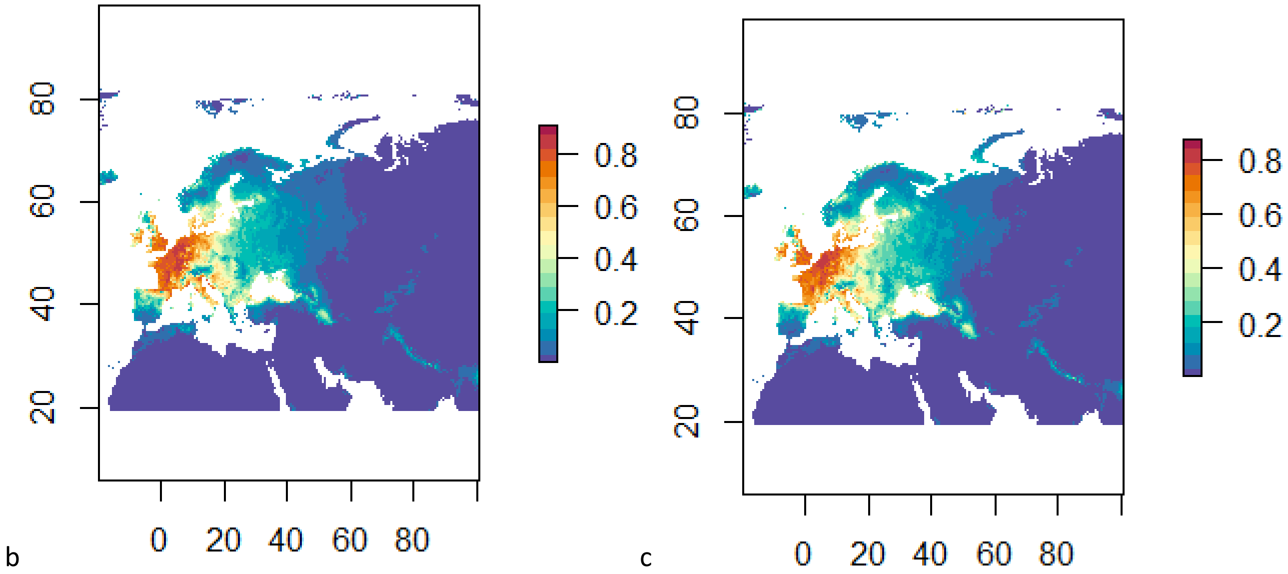


Figure 45b and 45c: Results of the simulation for winter 2021-40 (b) and 2041-60 (c)

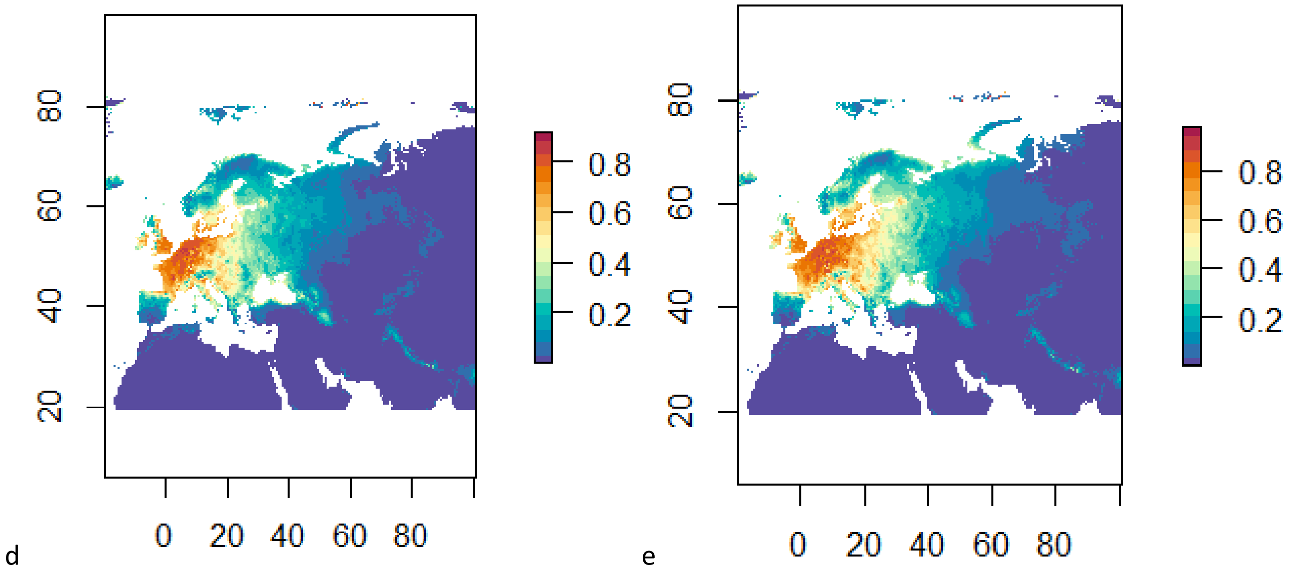


Figure 45d and 45e: Results of the simulation for winter 2061-80 (d) and 2081-2100 (e)

Novel points

In *Figure 46* it can be observed that regions predicted to have the most adapt conditions, under an environmental variable point of view, are located in central east Europe, Scandinavia and Russia.

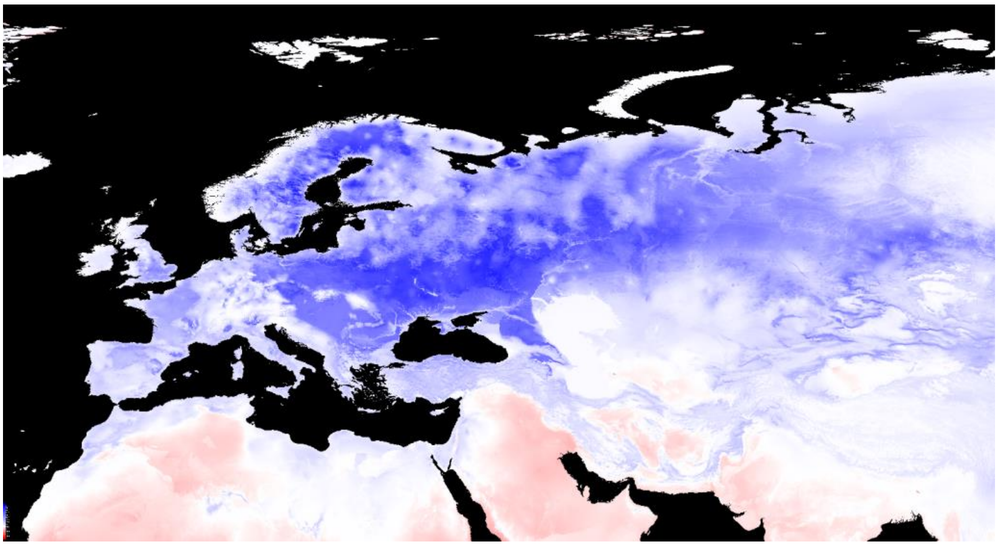


Figure 46: novel point in the hotlayers climate conditions: winter 2081-2100

Spatula querquedula (Garganey)

Present and forecasted summer

Suitability maps

The Maxent model for the distribution in summer for the species *Spatula querquedula* resulted in an Area Under Curve (AUC) of 0.857, testifying a good predictive performance. From the present map (Fig. 47a) it can be seen that the territories with the higher probability of being suitable for *Spatula querquedula* are located in France and the Netherlands, with a few patches along Black and Caspian Seas, in addition. Moving onto the following twenty-years modelled periods (Fig. 47b-e), red areas are observed to shift toward higher latitudes, through central Europe, reaching the Scandinavian peninsula and the expanding over Russian flatlands and coasts facing the Arctic Ocean.

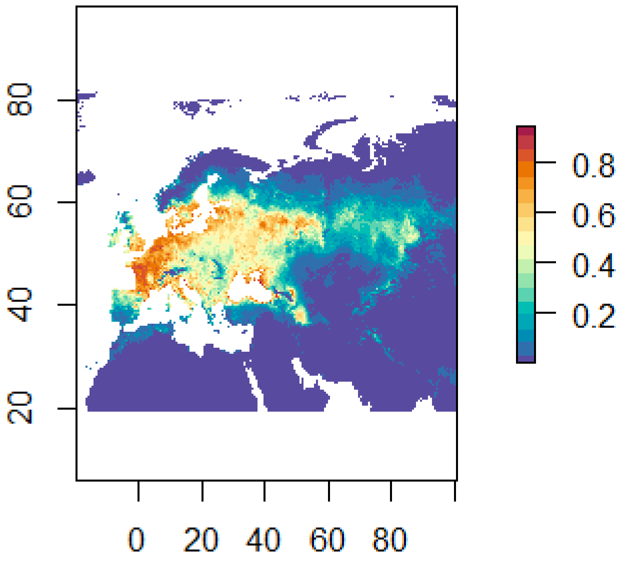
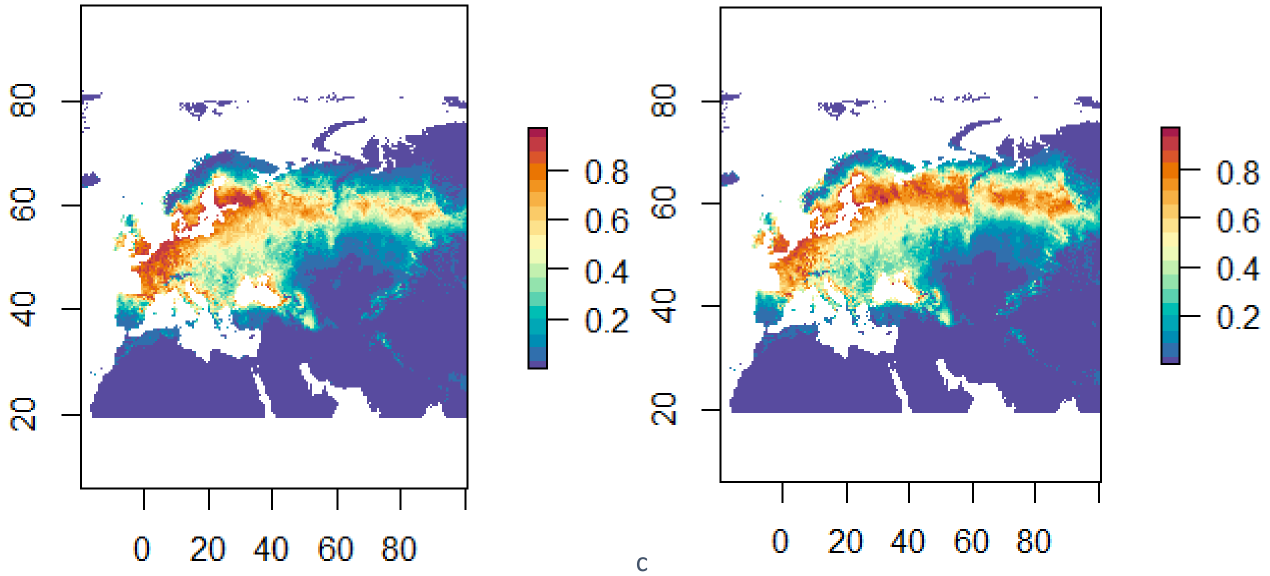


Figure 47a: representation of the Maxent model for present situation



b

c

Figure 47b and 47c: Results of the simulation for summer 2021-40 (b) and 2041-60 (c)

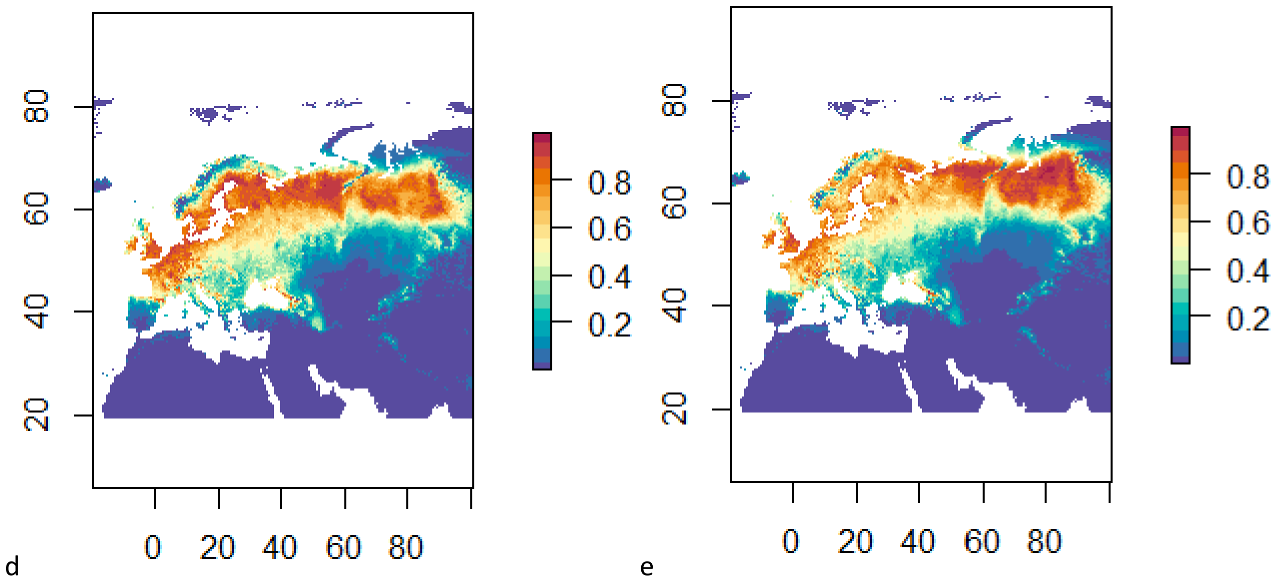


Figure 47d and 47e: Results of the simulation for summer 2061-80 (d) and 2081-2100 (e)

Novel points

According to the previous picture (Fig. 48), the predicted areas in which there would be the highest overlay of considered environmental and bioclimatic variables by the end of the century are mainly located over east Europe and Russian flatlands. To these, dark blue regions appear also in Scandinavia, Murmansk peninsula, and Russian coastal areas. Red novel points correspond with arid and desertic habitats.

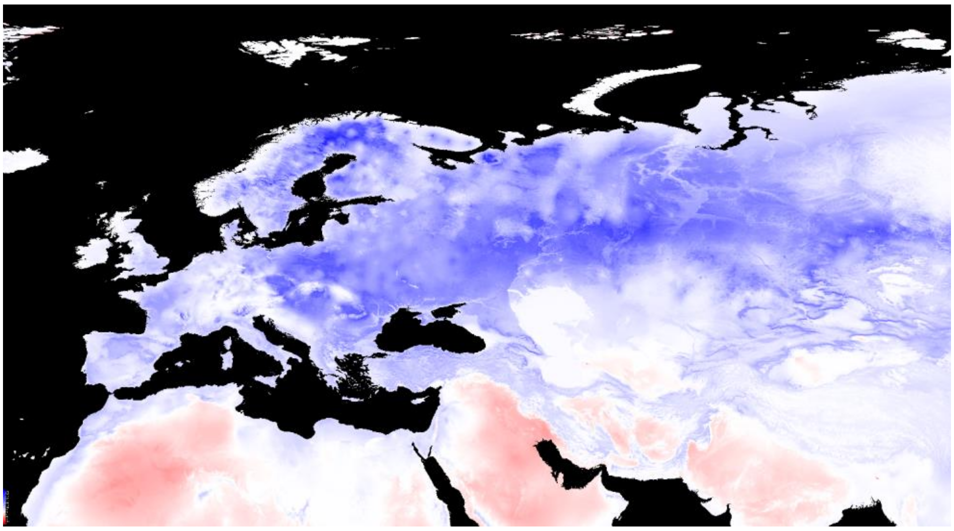


Figure 48: novel point in the hotlayers climate conditions: summer 2081-2100

Present and forecasted winter

Suitability maps

The Maxent model for the distribution in winter for the species *Spatula querquedula* resulted in an Area Under Curve (AUC) of 0.921, testifying a good predictive performance. According to the present suitability map (Figure 49a), the territories with the highest probability to be characterised by optimal environmental and climatological parameters for *Spatula querquedula* species are located in France and Italy, in particular in the correspondence of the Venice lagoon. The predictions regarding farther scenarios (Fig. 49b-e) show that central European countries (Germany in particular), could be expected to evolve in more and more suitable territories. By the end of the century, it is predicted that all central Europe would present extremely high probability of being suitable for this species. Territories outside this boundaries show a medium-low probability, while outside the European borders, very few areas seems to become more suitable. Italy and, in particular, the Po Valley, is among the territories with the highest predicted suitable conditions.

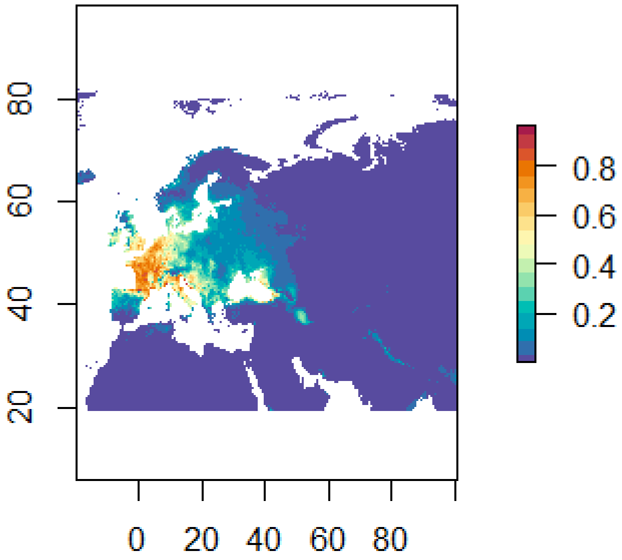


Figure 49a: representation of the Maxent model for present situation

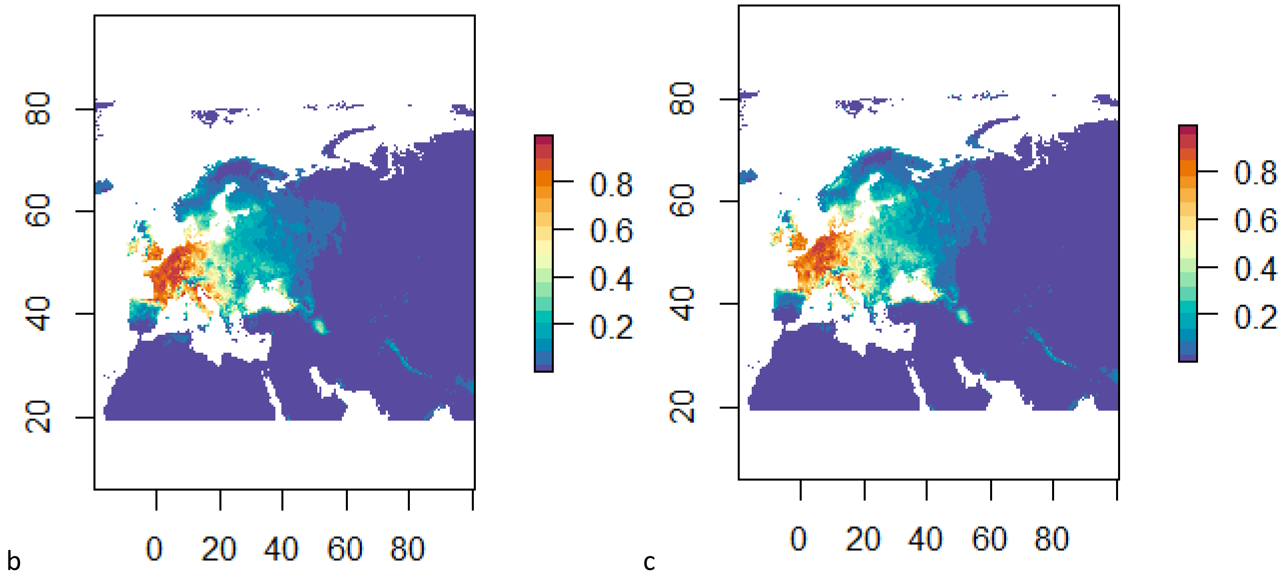


Figure 49b and 49c1: Results of the simulation for winter 2021-40 (b) and 2041-60 (c)

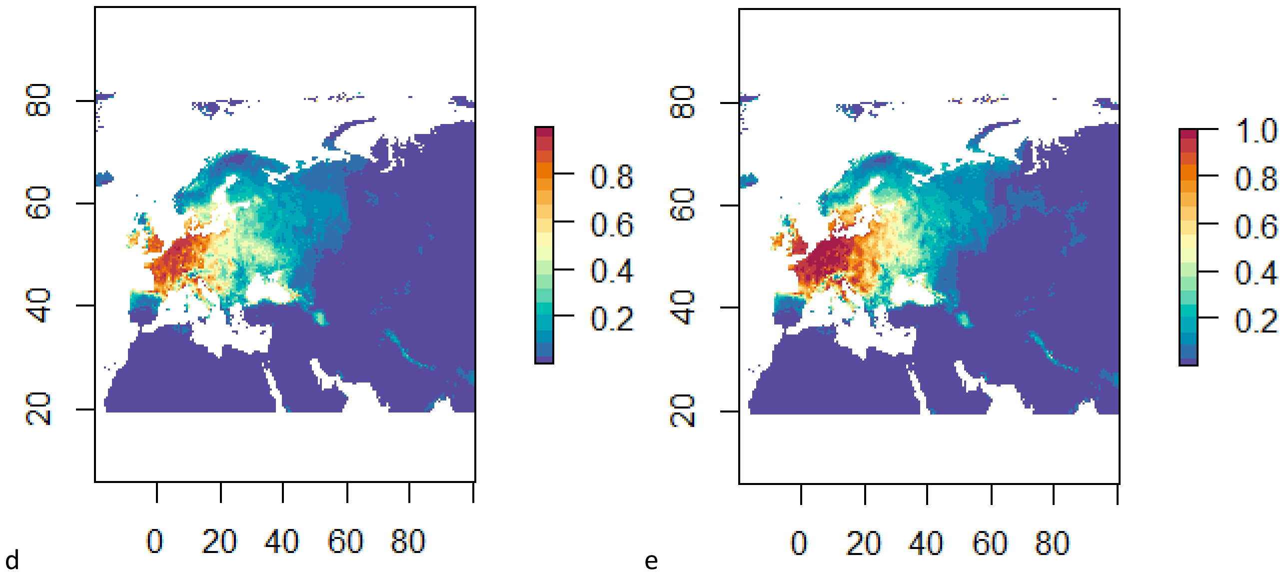


Figure 49d and 49e: Results of the simulation for winter 2061-80 (d) and 2081-2100 (e)

Novel points

In *Figure 50* are shown the areas with the predicted overlay of the considered variable by the end of the century, strictly in mathematical terms. The areas indicated with dark blue colour correspond to the highest overlay. Therefore, it appears that Sweden and Finland, eastern Europe, and a wide area over Russia would present the majority of conditions which fall within the range of accepted parameters characterising the fitness of the species. Novel points are consistent with dark blue areas of the suitability map (Figure).

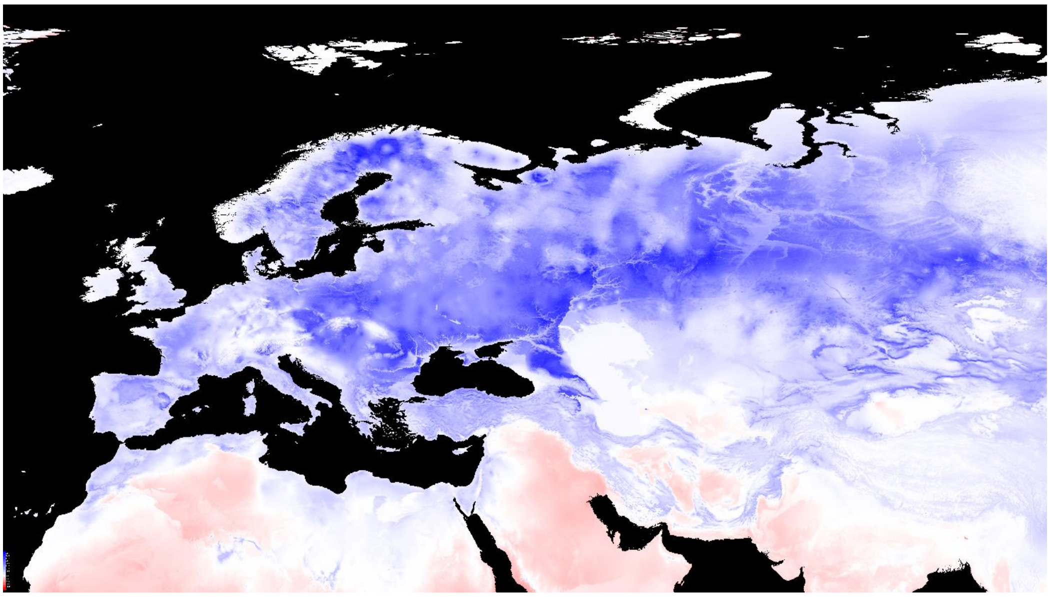


Figure 50: novel point in the hotlayers climate conditions: winter 2081-2100

Discussion

The main objective of this thesis was to estimate if and how the migratory routes of nine aquatic wintering anatids may be undergoing a modification in response to climate change. All the species analysed are following the Black Sea-Mediterranean Flyway, during their migratory movements, in the central-Mediterranean region. Considering the environmental conditions of the present, this research highlighted the interaction between the characteristics of the considered migratory species and the environmental variables that define their suitability conditions. Subsequently, these interactions were reconsidered given the predicted conditions of future climate scenarios, both in the medium and long term, identifying with the Maximum Entropy approach the possible changes in the areas suitable for the presence of anatids.

Western Palearctic ducks are among the bird species for which changes in geographic distribution have been especially well documented, generally occurring through short-stopping of the migration process leading to northeastern shifts in breeding ranges. Such a process largely occurs through a shortening of the autumn migration journey, so that sites formerly used for autumn migration stopover or those that host just few individuals at the northern or eastern edges of the breeding range will become increasingly important, sometimes even hosting birds that have become resident (Anthony D Fox et al. 2016).

Observing the nine analysed species predicted outcomes, it can be seen some similarities among the species depending on the plot under examination. According to the predicted suitability maps, the nine species can be divided into two groups, given the expected probability distribution similarities, based on bioclimatic variables and maximum temperature predicted conditions for all the twenty-year scenarios.

Anas acuta, Anas crecca, *Anas platyrhynchos*, *Aythya ferina* and *Aythya fuligula* are predicted to face similar distribution pattern of their territories with higher suitability, for both summer (breeding) and winter (wintering) seasons. As expected, for summer seasons in future scenarios, more and more territories at higher latitudes are predicted to become more suitable for these species. The importance of boreal wetlands (lakes, ponds, rivers, swamps) for breeding ducks can be forecasted to likely increase in some areas as changes in adjacent biomes make the latter less hospitable (Holopainen et al. 2015). Higher expected temperature due to climate change (Anand et al., 2022) would ensure more favourable conditions in territories like Scandinavia, Siberia, and Arctic Ocean islands. These territories are already nowadays strategic areas for breeding season of duck species as a lot of other animal species. Given the increasing importance these areas are expected to gain by the end of the century, more attention from institutions, policy makers, and stakeholders is needed, with the aim to guarantee the preservation and development of the boreal biome (Holopainen et al. 2015). Furthermore, changes in boreal habitat would differently affect the species, given the relative niches characterising each of them; for example, *Anas crecca* more frequently use smaller lakes than bigger ones while pair density in *Anas platyrhynchos* increases with shoreline—lake area ratio. In addition, dabbling ducks prefer shallow lakes (Holopainen et al. 2015).

On the other hand, winter season scenarios projections, over the study area, show a wide homogenously spread probability distribution for all these five species, with no significant extremely favourable conditions peaks. It is predicted that, by the end of the century, a lot of areas at high latitudes would present better suitable conditions than the current period. This is consistent with the expected higher mean temperature scenario predicted by the SSP585, especially due to the fact that the areas on the planet that will face the most intense warming are the Poles (Pirani et al. 2024). Since wintering areas are located at temperate latitudes, the focus is on Mediterranean Sea shoreline and Middle East, until India's borders. For all these species suitable areas are predicted to occur over these countries, but experiencing higher temperature could become a limiting factor for their fitness. It is therefore in the novel points plots those areas in which at least one variable among the considered (bioclimatic and maximum mean temperature) is shown to cross over the idoneous physiological boundaries. Red areas indeed are located very close to the predicted suitable coastal areas of African countries bordering the Mediterranean Sea, the Persian Gulf, and Indian Ocean. Even if those areas do not overlay, the need to consider them as vulnerable to climate changes is clear, and, therefore, particular strategies for wetland management, conservation, and protection are required, with the aim to guarantee the presence of such fragile ecosystems (as wetland are) for the maintenance of migratory flyways (Valizadeh et al. 2021).

As it concerns for the remaining four species, the suitability maps return very high probability distribution for the predicted suitable areas for both the current situation in the present and all the futures twenty-years scenarios. Similarities in suitable areas can be seen for both summer and winter predicted seasons. During summer months (breeding season), at current situation, most suitable climatic conditions appear to be present mostly in central European countries, and coastlines facing the North Sea. As expected, similarly to the *Anas* species analysed above, the same predicted northeast shift is evident. But for these species, predicted suitable conditions are very defined, therefore it could be assessed that, by the end of the century, breeding areas for *Mareca penelope*, *Mareca strepera*, *Spatula clypeata* and *Spatula querquedula* could be located prevalently at higher latitudes than it happens nowadays. This prediction is based only on bioclimatic variables and maximum mean temperature; taking into account more habitat features could be a possible solution in order to have deeper analysis. By focusing on climatic change only, our results can be used to identify areas where land-use decisions will be of critical importance for waterbird conservation.

On the other hand, wintering areas appear to be less spread all around European continent than in the case of the previous group of *Anas* species. Also, for winter season, territories with the predicted highest probability of present suitable conditions are precisely localised over few regions. Among these, the Po Valley, and, in particular, the Venice Lagoon is predicted to have extremely suitable characteristics, under a climatological point of view. Differently from the previous group, these species are not predicted to present suitable conditions for wintering areas way outside of European borders; there are areas with low probability values in Russia, and more predicted suitable conditions are indicated along Black Sea coasts. It, therefore, could be predicted that the main migratory flyway would be from the north coastal areas of Siberia (breeding season) to central Europe and European Mediterranean coastlines. It is therefore more and more essential to build up conservation, management, and improvement strategies to preserve wetland ecosystems in these regions, given the importance they are predicted to have for analysed *Anas* species conservation.

By comparing the predicted probability of an area to be suitable in farther scenarios for each species it can be observed some differences in the relationship between colours and their associated values. It is therefore observable that for the first five species (*Anas acuta, Anas crecca, Anas platyrhynchos, Aythya ferina, and Aythya fuligula*) red and dark red areas correspond to associated probability values of 0.6-0.7. On the contrary, for the last four species (*Mareca Penelope, Mareca strepera, Spatula clypeata, and Spatula querquedula*) dark red colours correspond to a probability close to 100% of predicted suitability. To explain this difference a few reasons could be taken into account; as first, it could indicate that the latter species are less generalists, and, therefore, perhaps more subject to a shift to the only areas where the suitability is expected to be greater. But it could also be an effect resulting from the smaller number of input data, or even from a very concentrated spatial distribution in some parts. However, it is difficult to say whether this concentration is representative of a real trend of the species concerned, or whether it is a sampling bias or a matter of data availability.

According to the performed analysis, for the species *Spatula querquedula* a focus should be highlighted. It is reported in the literature that the main territories of these population for wintering periods are located prevalently in the Sahel region, with relevant reported presence in India and southwest Asian countries.

Looking at the predicted suitability maps for future scenarios by focusing over Asian countries (since the Sahel region is only partially overlapping with the study area considered in this work), it seems no predicted suitable conditions would be present in such areas. Moreover, novel points output map returns those areas as relevant places in which predicted future conditions would not range within the acceptable fitness parameters thresholds for this species. This could be explained through the predicted increase of temperature which could make those territories inhospitable because some bioclimatic variables are expected to be no longer suitable. Therefore, a possible consequence might be that those territories won't be used anymore as wintering grounds by *Spatula querquedula* populations.

Nevertheless this hypothesis need to be better investigated, on one hand to check if the result of the model might have been affected by other confounding factors, and on the other hand to try understand which can be the fate of those lands and, consequently, of the species wintering there.

Under a technical perspective, the analyses of the accuracies and the performance of the model simulations also gives useful information to better frame the importance of the results. Among the bioclimatic variables and maximum temperatures which affects the nine species analysed, some similarities can be detected.

Looking at summer outputs for all the species, it can be observed that variable bio_17 (Precipitation of Driest Quarter) not only is the common variable among all the species affecting their suitability, but it is also the one with the most important role in determining the best conditions. Since it has the same relevance for all the three output of the jackknife (training gain, test gain and AUC) it means that it is the variable that better generalises, giving comparatively better results on the set-aside test data. In other words, this tells that precipitation of driest quarter variables help Maxent the most in obtaining a good fit to the training data, making the models that use them more transferable, and, therefore, more adapt to make predictions about future scenarios.

For *Anas acuta, Anas crecca*, *Anas platyrhynchos*, *Aythya ferina*, and *Aythya fuligula* other relevant variables are bio_9 (Mean Temperature of Driest Quarter) and bio_2 (Mean Diurnal Range (Mean of monthly (maximum temperature - minimum temperature)). This is consistent with what it was stated before since the northeast predicted shift toward higher latitudes it is expected to happen especially during summer months. Regarding *Mareca penelope*, *Mareca strepera*, *Spatula clypeata* and *Spatula querquedula* species, in addition to bio_17, other relevant bioclimatic variables are bio_10 (Mean Temperature of Warmest Quarter) and maximum temperatures for the months of May and September (tmax5 and tmax9). This is consistent with the other results since from May to September the highest temperatures are expected to come. Moreover, these two months correspond with the arrival (May-June) and the departure (September-October) of migration movements. Once more, it is therefore underlined the role of temperature as migratory input.

As it concerns wintering period, one relevant variable is bio_11 (Mean Temperature of Coldest Quarter). It comprehends all the nine species, because, for those with relevant variables as the maximum temperature for the months of December and January, mean temperature of coldest quarter comprehends those values. In addition, it is less vulnerable to monthly variation, taking into account the coldest three months. For *Anas acuta, Anas crecca*, *Anas platyrhynchos*, *Aythya ferina*, and *Aythya fuligula* species, another relevant bioclimatic variable is bio_7 (Temperature Annual Range), which is determined by the difference between the minimum temperature of the coldest month, and the maximum temperature of the warmest. The high sensitivity of the model to this variable is likely to be linked to the changes that climate change may have on the year-round patterns in terms of temperature range. The species we observe today certainly evolved with some physiological adaptations that make the organisms able to cope with some spikes of high temperature, as well as for troughs of very low temperature. To some extent, migration may be a behavioural adaptation that helps those species to find environmental conditions that always fall within the range of bearable temperature values. However, if a very quick variation in the frequency of the occurrence of such a spikes

will happen, this may severely affect both the behavioural adaptation and the physiological ones at least in the areas where the environmental values are likely to become outside of the values to which the species adapted in its evolutionary history.
Regarding *Mareca penelope*, *Mareca strepera*, *Spatula clypeata* and *Spatula querquedula* species, another bioclimatic variable in common among them is bio_17 (Precipitation of Driest Quarter) as for summer periods. It is consistent with the previous results since, those species spend winter period at lower latitudes, where it has already been experiencing drier winters in the last years. Since the predictions are based on the current climatic situation modelled against the predicted SSP585 scenario, it is expected that by the end of the century precipitation in winter would decrease continuously.

Overall, the results of this study provided new insights about the possible effect of climate change on migratory waterfowl, suggesting the possible consequences that a shift of the migratory routes might have on migratory ducks' distribution. Moreover, it confirms the usefulness of mathematical modelling to better understand and explore possible future trajectories in the conservation priorities, along with the crucial role played by accessible scientific data repositories and databases such as GBIF and WorldClim.
Nevertheless, some limitations of the present study must be mentioned. Given the fact that several authors had proved a strong influence of temperature and precipitation on species distributions (Anand et al., 2022), for the present study it was decided to run Maxent simulations based on bioclimatic variables (taken from WorldClim) and maximum mean predicted temperatures for each month, until the end of the century, depending on the previsions based on the SSP585 IPCC scenario. Therefore, our conclusions are based on crude climatic, temperature and drought predictors, and they do not consider the projected changes that may occur due to the potential negative impact of sea-level rise, drying of inland water bodies, physical habitat modifications and fluctuation on primary productivity and vegetation cover, and other anthropogenic impacts (Giunchi et al. 2019). Nevertheless, only focusing on climatic change, our results can be used to identify areas where land-use decisions will be of critical importance for waterbird conservation.
Sustaining migration hinges on our ability to maintain dynamism in both ecological processes and the associated wetland management practices that foster and maintain wetland ecosystems. To do so, it is needed the joint role of public–private wetland resources in supporting migratory waterbirds and highlight the importance of managing multiple ownerships as an integrated system (Donnelly et al. 2019).
According to Guillemain and Hearn (2017), since it is expected a northeast shift toward higher latitudes going farther to the end of the century, it is needed to evaluate whether the current status of protection about duck critical sites is sufficient in those regions where duck numbers are predicted to increase the most, driven by climate change, so as to highlight where to focus internationally coordinated efforts, in order to provide an efficient network of protected areas for ducks for farther future.
In addition, given the fact that species engaged in long migratory flights, as the case of ducks, during their annual cycle touch a great number of countries, their populations can be affected by factors occurring throughout the whole annual cycle. Therefore, to meet conservation targets, improvements to habitat used during one single period or season may not be sufficient if some habitats used during another part of the annual cycle is limiting (Lamb et al. 2020). This is the reason why international collaboration projects are needed, with the aim to create a stable network of stopover sites (perhaps larger than the existing Ramsar site network). These solutions could help to maintain stable or even increase populations of migratory species. On the other hand, the loss of habitat and the loss of network connectivity will negatively impact migratory bird populations (Si et al. 2018).
According to Xu et al. 2019, species which cover longer migration distances, or with smaller breeding ranges, or even with a smaller size of their non-breeding ranges compared to breeding ones, are predicted to

experience population declines more likely. By contrary, species with a relatively small body mass, short generation length, and large clutch size, should be less likely to decline.

On the other hand, wetlands are subject to numerous stressors and are threatened globally, especially in human-dominated environments. Among these stress factors expansion of arable land, land developed due to urbanization, sea level rise, and warming temperature which leads to higher evaporations rates have relevant role in ecosystem degradation and loss (Liu et al. 2020).

It has been demonstrated that high northern latitudes are experiencing climate change at an intensity of over twice the global average. This means that species that migrate to the norther areas could be particularly affected by those changes in territories corresponding to their breeding grounds. Most species are predicted to face changes by shifting their distributions, often towards poles or to even higher elevations; however, these shifts in northern breeding grounds distributions could result constrained by the Arctic coastline. Moreover, shifts towards northern latitudes are likely to be determined also by other factors, such as the phenomenon of 'shrubification' of tundra (in which the biome assumes characteristics of biomes typically occupying southern latitudes and more mild climate conditions) and northward expansion of predators.

In addition, shift north-eastwards of breeding grounds distribution might extend the migratory distance between suitable breeding and non-breeding habitat or push species far from their current migratory routes. If individuals need to fly further to reach suitable breeding habitat, they also must acquire more energy, in order to make a longer journey. This is another reason why protection of stopover sites is vital (Wauchope et al., 2017).

Among coastal systems, IPCC has identified estuaries, deltas, and small islands as the most vulnerable to climate change and sea-level rise hazards. Sea level rise, which is strictly related to climate change, will cause continued and more frequent inundation of low-lying areas, mainly where natural buffers and barriers have been removed. Inside the worst possible predicted scenario SSP585, the IPCC's Sixth Assessment Report considers, a mean global sea level rise between 0.63–1.01 m in the year 2100, and a range of 0.98–1.88 m to 2150.

According to these scenarios, another effect climate change may cause is a more intensified evapotranspiration which consequently leads to a water level drawdown and also more flood inundation, which could severely affect biogeochemistry, water quality and availability (Waddington et al., 2015).

Temperature is one of the most determinant factors that regulates wetlands biogeochemistry. Increased temperature, indeed, enhances the rate of biochemical processes. For example, the rate of nitrification, denitrification, nitrogen immobilization and organic phosphorus mineralization increases as temperature rises. Another direct effect of higher temperature may be an increase in both carbon dioxide and methane production within the wetland ecosystems themselves; on the contrary, an indirect opposite effect of rising temperature might be a reduction of aerobic respiration of organic matter since temperature reduces the capacity of the water column to hold oxygen in wetland ecosystem (Salimi et al., 2021).

Furthermore, degradation caused by drought, pollution, and saltwater intrusion is also threatening the health of coastal wetlands. Increasing temperatures leads to more severe phenomenon of eutrophication in coastal waters, that can influence wetland ecosystem by changing the structure of biotic communities (Genua-Olmedo et al., 2016).

Regarding the sea level rise, which is considered one of the main threats for coastal wetlands, scientific community opinion is still controversial, because wetlands can migrate landward if any barrier do not exist behind them, but this is often not the case. Wind waves have significant role in the erosion and loss of salt marshes at global level, especially at boundary zones. On the short term, extreme conditions, such as saltwater intrusion, droughts, or storm surges, may cause degradation and loss of both salt and fresh tidal water wetlands with more serious influence than slow sea level rise (Li et al., 2018). To promote the conservation and wise use of wetlands worldwide, the Convention on Wetlands (the Ramsar Convention) was signed in 1971 and was effective in detecting and declaring several sites of great importance for migratory and aquatic birds. Nevertheless, this has remained the only international agreement focused on wetlands to date. Although the Ramsar Convention aims to ensure the conservation of wetlands worldwide, many sites have little or no protection from national governments, and cases of wetland loss or degradation were reported continuously after the establishment of the Convention (Xi et al., 2021).

Since the entry into force of the Convention, more and more wetland sites entered the Ramsar protected areas, but it is still a small percentage of the whole global amount. Moreover, Ramsar distribution and, consequently, policies adoption for wetland conservation and restoration projects, are more developed in the richest countries. Among the above-mentioned sites, Camargue and Turkey example are reported. In 1994, Turkey ratified the Ramsar Convention and designated its first five Ramsar Sites. Later in 2002, Turkey further elaborated its wetland conservation strategy with the ‘Regulation for Protection of the Wetlands’. A National Wetlands Commission (NWC) was established to plan the country’s rational use, management, and conservation of wetlands. In 2021, Turkey had designated 14 wetlands as Ramsar Sites and 56 wetlands were protected by national laws (Arslan et al., 2023).

As it concerns the case of Camargue, this region is extremely vulnerable to flooding, since about 70% of the region lies within 1 m above mean sea level. In the second half of the 19th century, dykes were built in order to prevent its southern coastal regions from floods, but the main consequence was instead a reduction in sediment inflow which affected the formation of dunes and increased coastal erosion. Sea level rise, due to climate change, have accelerated these changes. In Camargue region, since 1961, the annual maximum observed sea-level height increase was up to 4 mm/year, and it was associated with strong winds pushing seawater toward the coastline. Progressively, coastal erosion reduced the beach width and made hydrodynamics phenomena stronger (Davranche et al., 2024).

The Conservatoire du Littoral, which is a public organization with the scope to protect coastal areas in France, promotes an ecosystem-based management process for Camargue wetlands, which follows a well-defined adaptive management plan. Among the main objectives of this management strategy, a pivotal point is, indeed, to increase resilience against sea level rise and coastal erosion themselves. Among the obtained outcomes of the restoration of natural flooding patterns, it has been favoured the development of halophilous vegetation; those species are important since they improve salt marsh ecological functioning and its stability, given the fact that the loss of this particular vegetation, characteristic of wetland ecosystems, is likely to strengthen the effects sea level rise has on coastal marshes (Davranche et al., 2024).

As it concerns the case of Venice lagoon, with a predicted vulnerability due to the combined effect of sea level rise and subsidence, engineering work of MoSE would be active for longer time in the next future, and it is not excluded that it could become a stable barrier between sea and Venice lagoon (Mel et al. 2021). To foresee what could be the functioning of a lagoon separated from the sea and deprived of its rivers, in a climate that will be increasingly warmer, we must carefully understand the ecology of coastal enclosed waterbodies such as coastal lakes and intermittently closed and open lakes and lagoons present along the warmer Mediterranean, South American, and Oceania coasts. Microbial metabolism, carbon cycle, and water balance of these lagoons must be deeply studied and understood, with the aim to fill the present scientific knowledge gap, also in the perspective of the closure of the Venetian lagoon. Knowledge and practices derived from the historical management of the extensive Venetian fish farms should also be carefully considered and enhanced (Tagliapietra and Umgiesser 2023).

Different conservation and management strategies are already being studied and implemented, differentiating in restoration projects (Sfriso et al. 2021), multidisciplinary approaches for conservation measures (Boscolo Brusà et al. 2022), and through projects devoted, making this habitat fate of public interest. But the preservation of wetlands is costly, and, due to the lack of financial resources, the resulting limited investments determine preservation strategies usually sub-optimally produced by Governments and Societies. At the base of such sub-optimal production there generally is an underestimation of the true value of wetland ecosystems and their related ecosystem services, which can instead balance their conservation costs (Stocco et al. 2023). Policymakers need to consider social costs and benefits, EU targets, and environmental concerns, which need innovative integrated management perspective, with the aim to implement cost-effective preservation and conservation strategies. Although a number of studies already exist that consider the importance of biodiversity conservation, together with the holistic perspective of the ecosystem services approach as a fundamental tool for coastal management, in the case of the Venice Lagoon as in other coastal contexts all around the world, the prioritization of coastal ecosystem functions and services, as priority policy- and decision-makers targets, has not received the deserved attention so far (D'Alpaos and D'Alpaos 2021).

As a result, projects aimed at restoring, conserving, and maintaining biodiversity are often implemented on a very small, local scale. However, these efforts may not significantly contribute to the conservation goals necessary to support waterfowl populations and migratory waterbirds, especially in future with increasing threats from climate change.

Conclusion

The main objective of this thesis was to estimate if and how the migratory routes of nine aquatic wintering anatids may be modified in response to climate change in order to discuss final results considering the consequences for the conservation of biodiversity.

The two main conclusions coming from this thesis are the following: breeding territories occupied by migratory waterfowl during summer months are predicted to shift toward higher latitudes, following the expected gradual mean temperature increase according to the SSP585 scenario drawn up by IPCC. Moreover, expected increasing temperature could make migrations toward tropical regions shorter in time, given the fact that those regions are predicted to become less suitable moving onto the end of the century, under a bioclimatic and temperature variables projection. The consequence of this would be that wetland coastal regions that border on seas (Mediterranean, Baltic, and Black Seas, in addition to Arctic Ocean) would become more and more important wintering sites, instead of stopovers, potentially leading to the cease of migratory movements.

One of the consequences of that is, starting right now, instead of overcoming wetland loss, the conservation challenge appears to lie in the maintenance of existing wetland ecosystem properties and its conformation on specific habitat needs of migratory waterbirds.

The factors influencing population declines in migratory species, including migration distances and habitat characteristics, are evidently facing various threats that include urbanisation, sea-level rise, and temperature increases. Moreover, predicted increase in sea level and the effects on the ecology of coastal enclosed water bodies, like Mediterranean lagoons, may further impact coastal ecosystems, leading to degradation and loss.

Indeed, it appears of the utmost importance to sustain migration through the trans frontier conservation of wetland ecosystems. This would require cross-borders joint efforts, likely involving public and private resources, to support waterbirds and emphasises the importance of managing multiple ownerships as an integrated system. On the one hand, cooperation must be triggered to face the high costs associated to preserving wetland ecosystems; on the other hand, cross-borders policy making to conserve coastal ecosystems and wetlands should be considered as a tool to ensure equity and the even distribution of all the ecological functions and processes that are today linked also through birds' migration patterns.

Gaining a deeper understanding of the relationship between habitat use, populations density, biodiversity and ecosystem services related to them is of high importance, to ensure a good future not only for migratory birds, but also for crucial ecosystems and their ecological functions.

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Annex I

Models technical evaluation

Model for Anas acuta

Summer:

AUC

The plot in *Figure S1* verifies how much the model analysis is accurate. The red (training) line shows the “fit” of the Maxent model to the training data. The blue (testing) line indicates the fit of the model to the testing data and is the real test of the model’s predictive power. The black line shows the expected line if the model was no better than random. It can be noticed that the training data is AUC=0.712, thus higher than AUC=0.5 (random prediction). It means that the model performs better than a random model would. The farther towards the top left of the graph that the blue line is, the better the model is at predicting the presences contained in the test sample of the data.

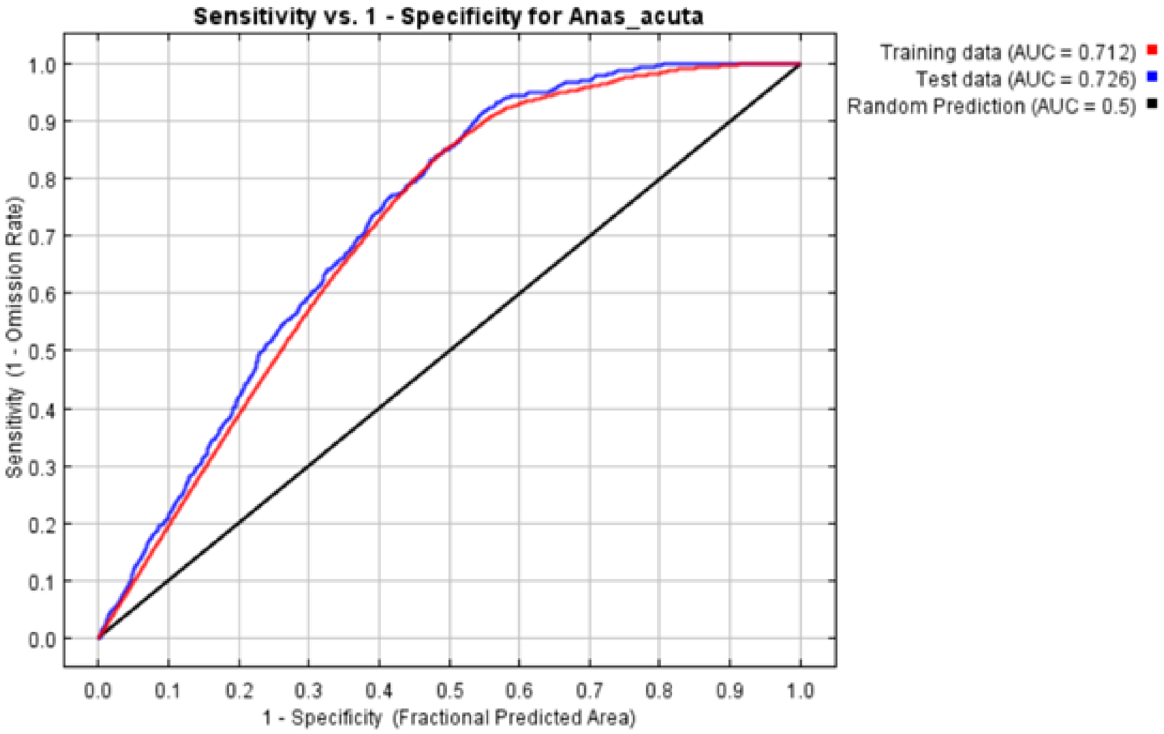
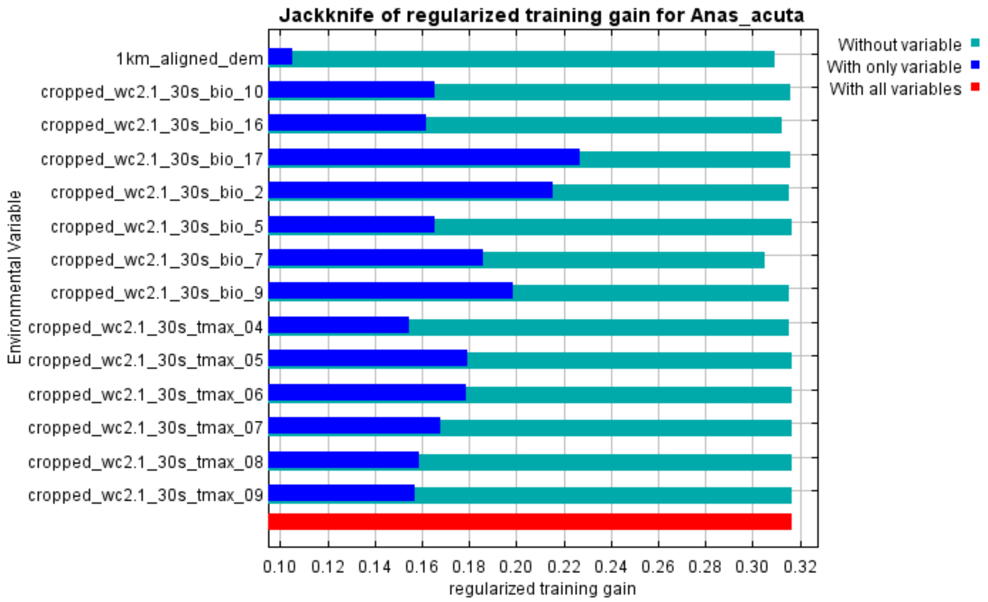


Figure S1: AUC plot for Anas acuta summer model

Jackknife

The next picture (Fig. S2) shows the results of the jackknife test of variable importance. The environmental variable with highest gain when used in isolation is bio_17 (precipitation of driest quarter), which therefore appears to have the most useful information by itself. Other efficient variables are bio_2 (mean diurnal range) and bio_9 (mean temperature of driest quarter). The environmental variable that decreases the gain the most when it is omitted is bio_7 (temperature annual range), which therefore appears to have the most information that isn't present in the other variables. Regarding all the other light blue lines, none of the environmental variables used contain useful information that is not included in other variables; therefore, a single omission of each variable does not shorten the light blue lines a lot.



FigureS2: Jackknife of regularized training gain for Anas acuta summer

Winter:

AUC

From the following plot (Fig. S3) it can be seen the model used performs better than a random model, given the AUC value of 0.675, as for all models for winter season for *Anas acuta* species.

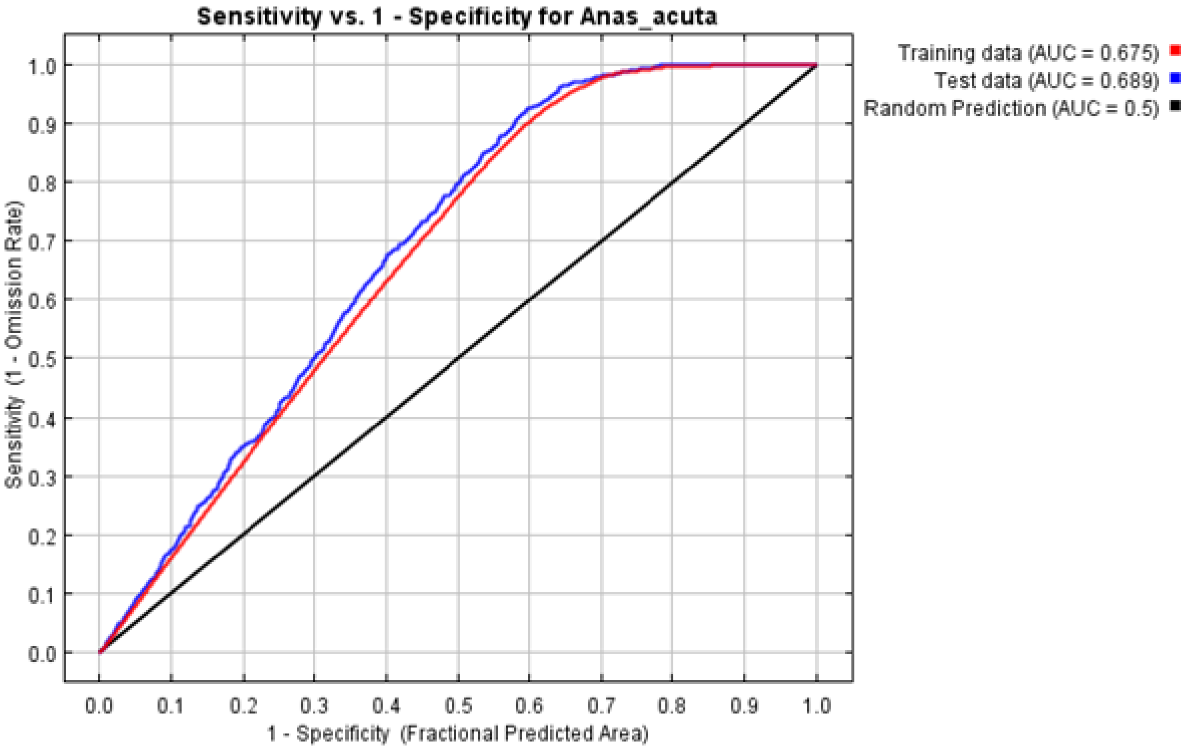


Figure S3: AUC plot for Anas acuta winter season

Jackknife

Having a look at the most relevant variables affecting the changes in suitability conditions for *Anas acuta* in winter the Jackknife test (Fig. S4) of regularised training gain returns that bio_7 seems the variable impacting the most. Looking also at the Jackknife of test gain and for AUC two other variables seem to have important impact, bio_11 (Mean Temperature of Coldest Quarter) and tmax.12 (maximum temperature in December). The least useful information is bio_2 (Mean Diurnal Range). On the other hand, the light blue lines show that none of the environmental variables used contain really useful information that is not included in other variables, a single omission of each variable does not shorten significantly the light blue line. However, the environmental variable that decreases the gain the most when it is omitted is bio_16 (precipitation of wettest quarter), which therefore appears to have the most information that isn't present in the other variables (light blue line).

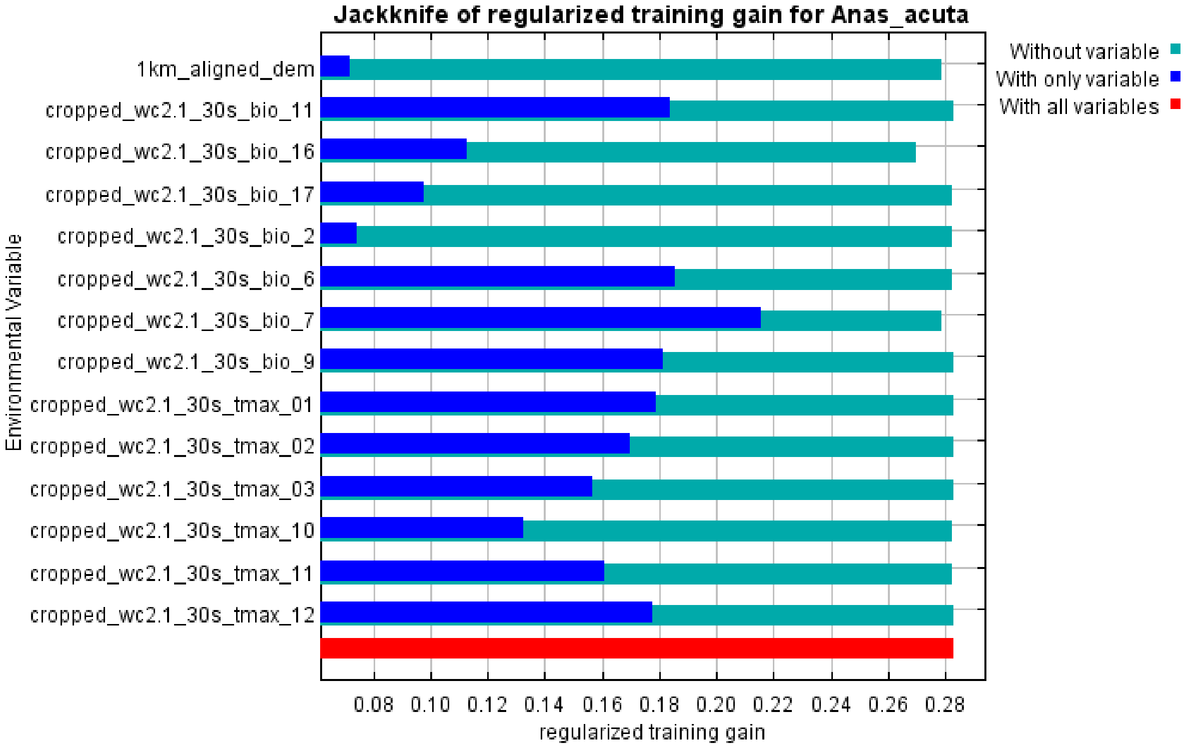


Figure S4: Jackknife of regularized training gain for Anas acuta winter

Model for Anas crecca

Summer:

AUC

From the following plot (Fig. S5) it can be seen the model used performs better than a random model, given the AUC value of 0.592, as for all models for summer season for *Anas crecca* species. This means the resulted model is quite appropriate, even though it doesn’t perform so efficiently.

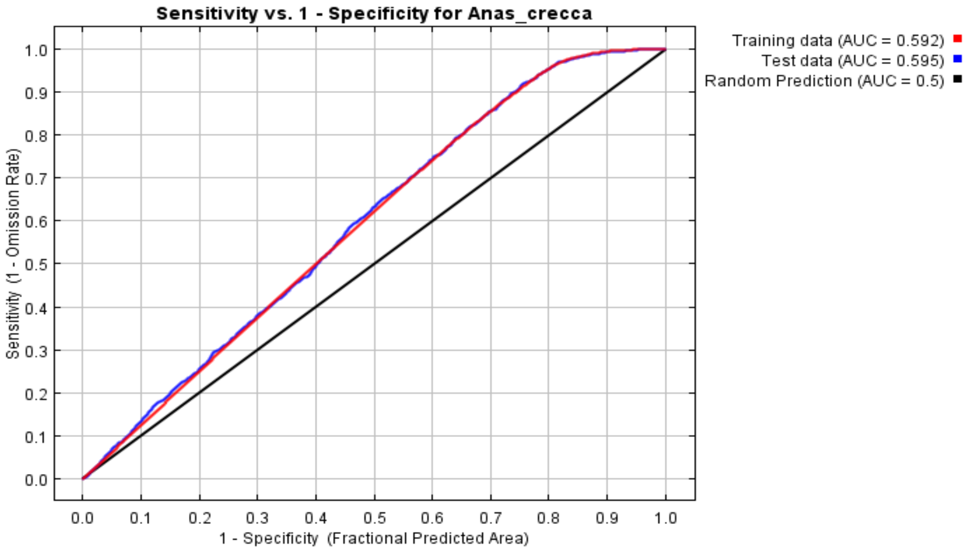


Figure S5: AUC plot for Anas crecca summer season

Jackknife

The following picture (Fig. S6) shows the results of the jackknife test of variable importance. The environmental variable with highest gain when used in isolation is bio_17 (precipitation of driest quarter), which therefore appears to have the most useful information by itself. Other efficient variables are bio_2 (mean diurnal range) and bio_9 (mean temperature of driest quarter). The environmental variable that decreases the gain the most when it is omitted is bio_7 (temperature annual range), which therefore appears to have the most information that isn't present in the other variables. Regarding all the other light blue lines, none of the environmental variables used contain useful information that is not included in other variables; therefore, a single omission of each variable does not shorten a lot the light blue lines.

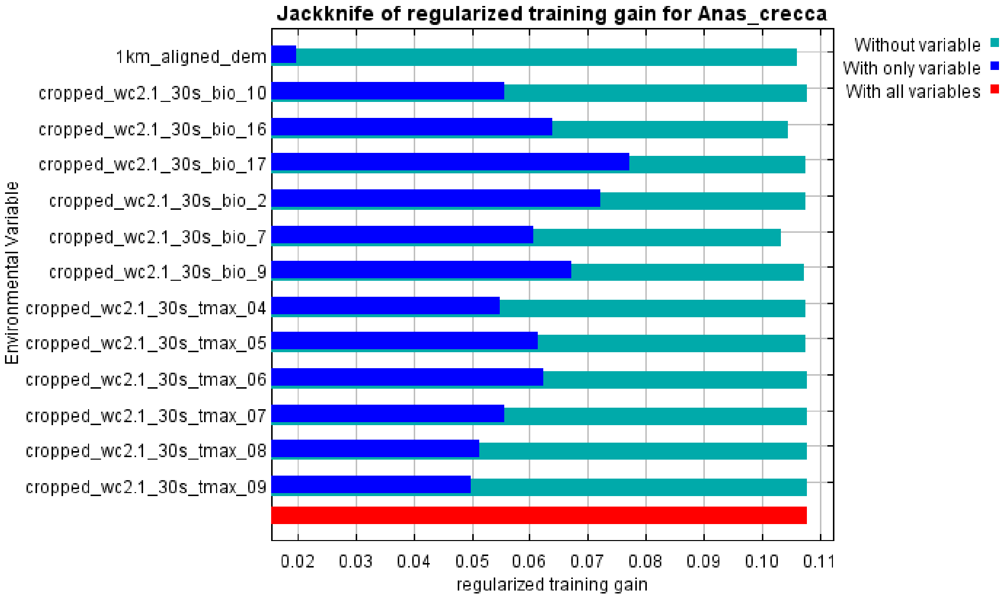


Figure S6: Jackknife of regularized training gain for Anas crecca summer

Winter:

AUC

From the following plot (Fig. S7) it can be seen the model used performs better than a random model, given the AUC value of 0.599, as for all models for winter season for *Anas crecca* species.

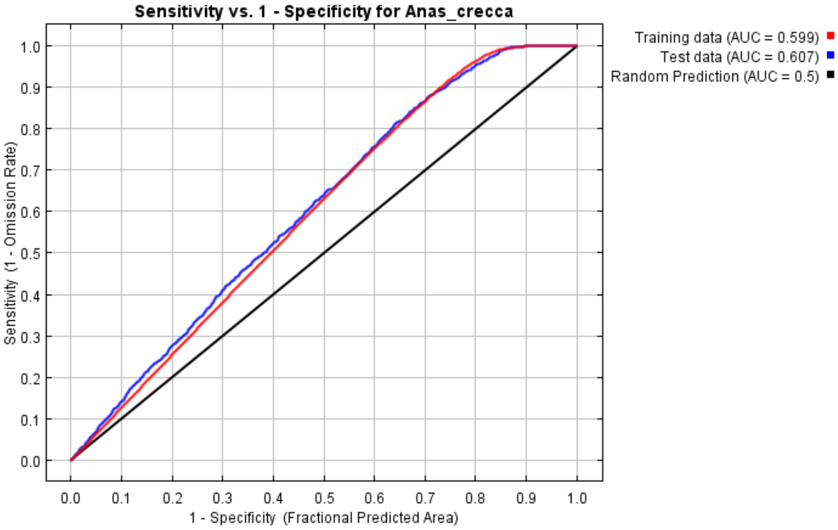


Figure S72: AUC plot for Anas crecca winter season

Jackknife

Looking at the most relevant variables affecting the changes in suitability conditions for *Anas crecca* in winter the Jackknife test (Fig. S8) of regularised training gain returns that bio_7 seems by far the variable impacting the most. Comparing the results of the Jackknife of test gain and for AUC also bio_11 (Mean Temperature of Coldest Quarter) and tmax.12 (maximum temperature in December) seems to have important impact. The least useful information is bio_2 (Mean Diurnal Range). On the other hand, the light blue lines show that none of the environmental variables used contain really useful information that is not included in other variables. However, the environmental variable that decreases the gain the most when it is omitted is bio_16 (precipitation of wettest quarter).

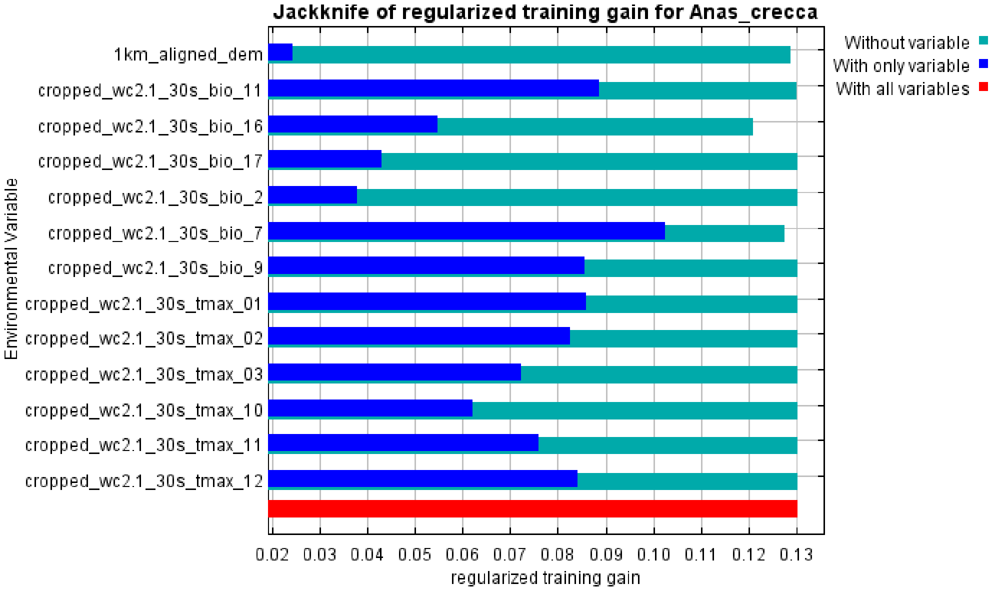


Figure S8: Jackknife of regularized training gain for Anas crecca winter

Model for Anas platyrhynchos

Summer:

AUC

From the AUC plot (Fig. S9) it can be seen the model used performs slightly better than a random model, given the AUC value of 0.532, as for all models for summer season for *Anas platyrhynchos* species.

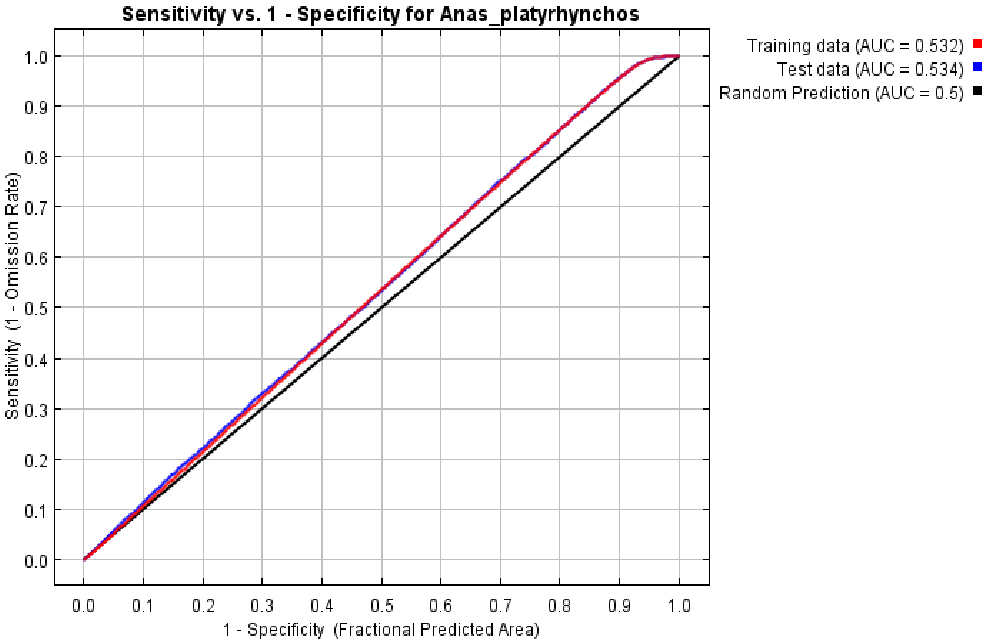


Figure S9: AUC plot for Anas platyrhynchos summer season

Jackknife

The environmental variable with highest gain when used in isolation is tmax_05 (maximum temperature in May) and bio_16 (precipitation of wettest quarter) (Fig. S10). Having a look also to the jackknife of AUC the most relevant variable is reported to be bio_17 (precipitation of driest quarter), followed by bio_2 ((mean diurnal range) and bio_9 (mean temperature of driest quarter). These outcomes are more consistent with the ones of the other species for summer periods. In this plot the environmental variable that decreases the gain the most when it is omitted is bio_7 (temperature annual range), while in the AUC jackknife is bio_17 by far. (jackknife of AUC can be found in the supplementary materials).

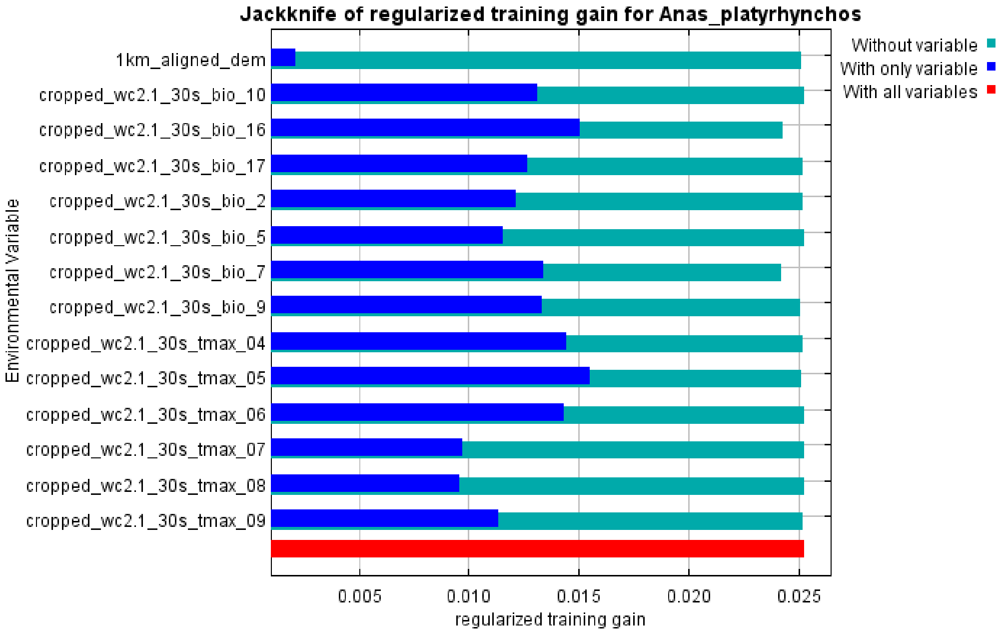


Figure S10: Jackknife of regularized training gain for Anas platyrhynchos summer

Winter:

AUC

From the AUC plot (Fig. S11), as it was already observed for summer months, it can be seen the model used performs slightly better than a random model, given the AUC value of 0.539, as for all models for winter season for *Anas platyrhynchos* species.

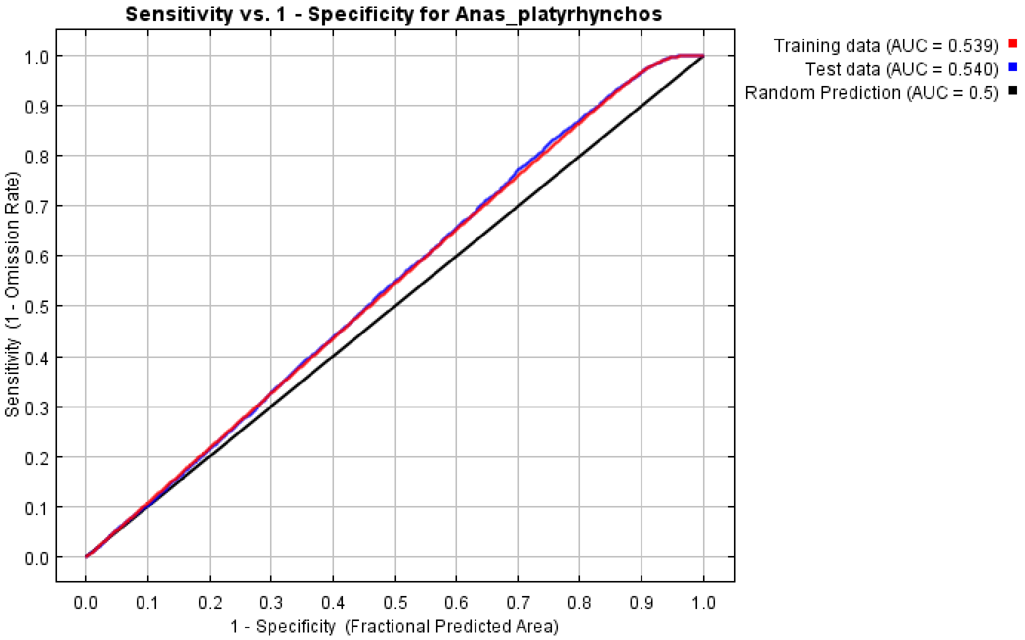


Figure S11: AUC plot for Anas platyrhynchos winter season

Jackknife

Looking at the most relevant variables affecting the changes in suitability conditions for *Anas platyrhynchos* in winter the Jackknife test (Fig. S12) of regularised training gain returns that bio_7 seems by far the variable impacting the most while the least useful information is bio_2 (Mean Diurnal Range). On the other hand, the light blue lines show that none of the environmental variables used contain really useful information that is not included in other variables. However, the environmental variable that decreases the gain the most when it is omitted is bio_16 (precipitation of wettest quarter).

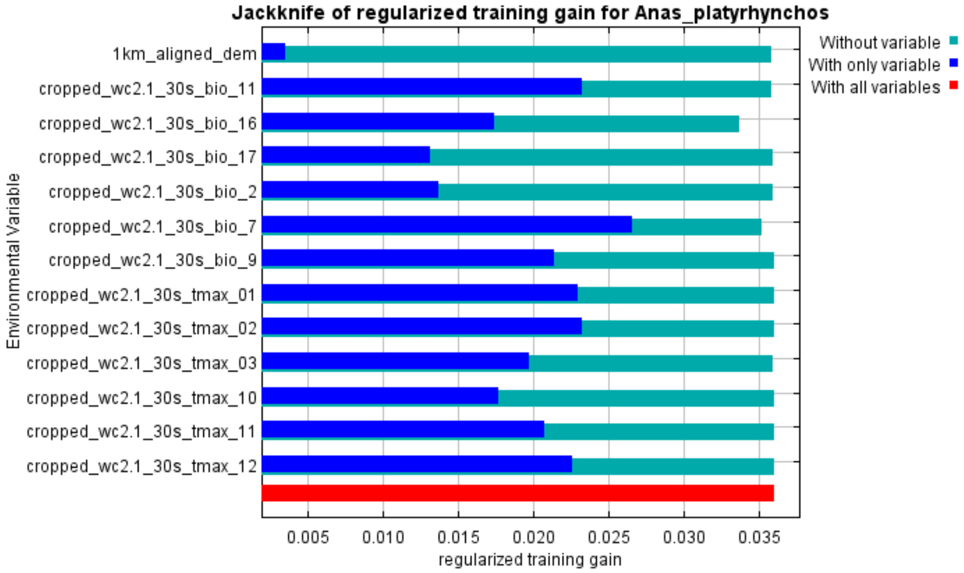


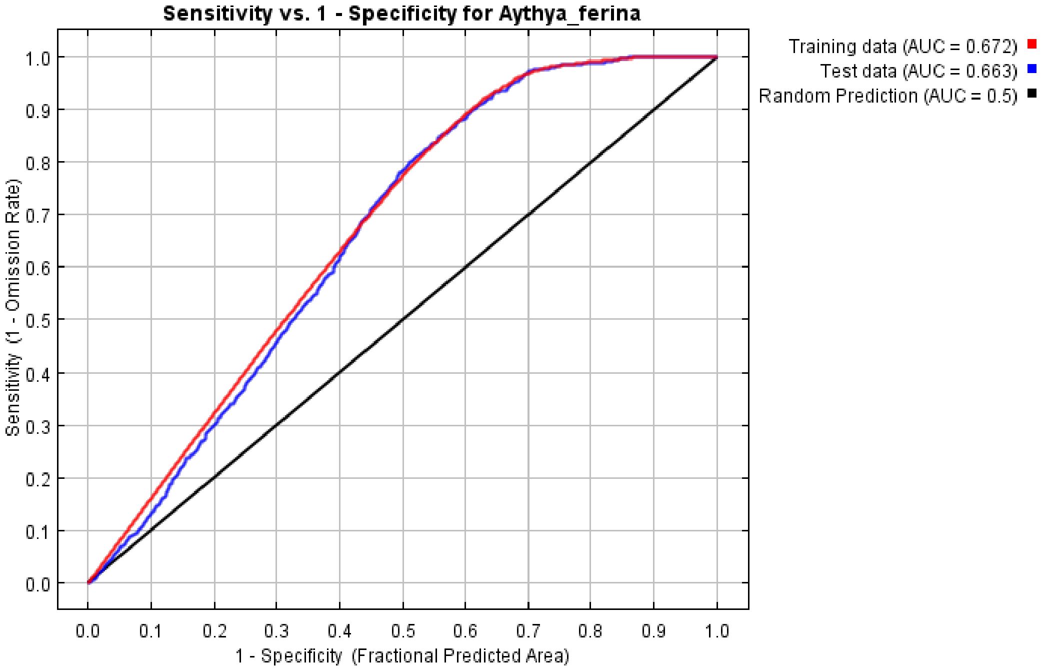
Figure S12: Jackknife of regularized training gain for Anas platyrhynchos winter

Model for Aythya ferina

Summer:

AUC

The AUC plot (Fig. S13) shows that the model used performs better than a random model would, given the AUC value of 0.672, for summer season of *Aythya ferina* species.



FigureS13: AUC plot for Aythya ferina summer season

Jackknife

For the case of *Aythya ferina*, the environmental variable with highest gain when used in isolation is tmax_05 (maximum temperature in May) and tmax_04 (maximum temperature in April). Looking also at the jackknife of AUC the most relevant variable is reported to be bio_9 (mean temperature of driest quarter) followed by bio_17 (precipitation of driest quarter) and bio_2 (mean diurnal range). These outcomes are more consistent with the ones of the other species for summer periods. In this plot (Fig. S14) the environmental variable that decreases the gain the most when it is omitted is bio_7 (temperature annual range), also for the AUC jackknife (jackknife of AUC can be found in the supplementary materials).

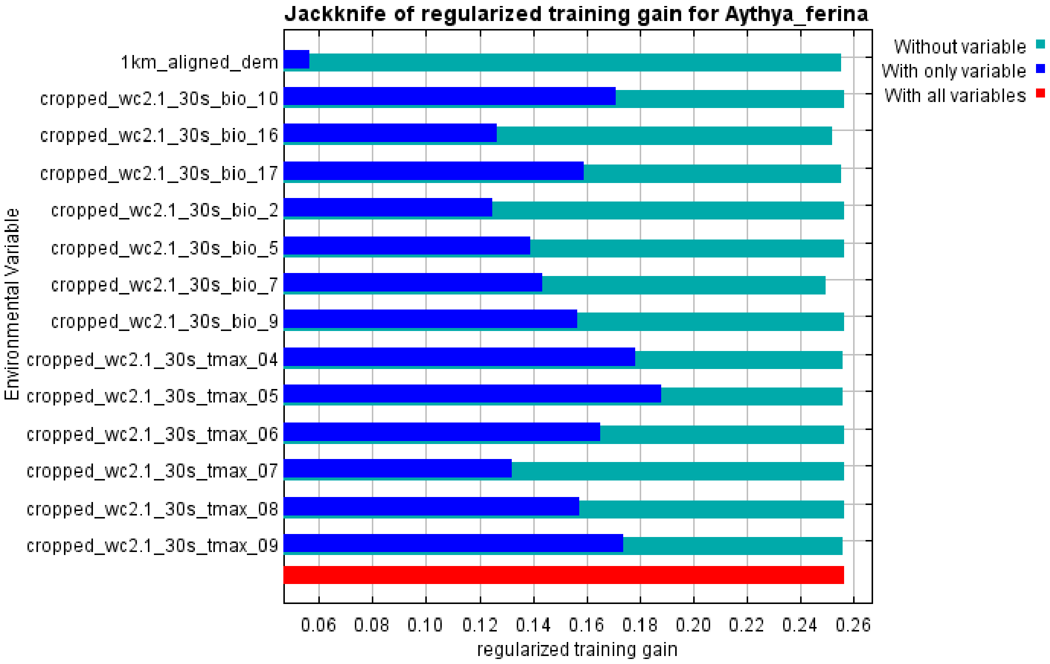


Figure S14: Jackknife of regularized training gain for Aythya ferina summer

Winter:

AUC

The AUC plot (Fig. S15) shows that the model used performs better than a random model would, given the AUC value of 0.648, for winter season of *Aythya ferina* species.

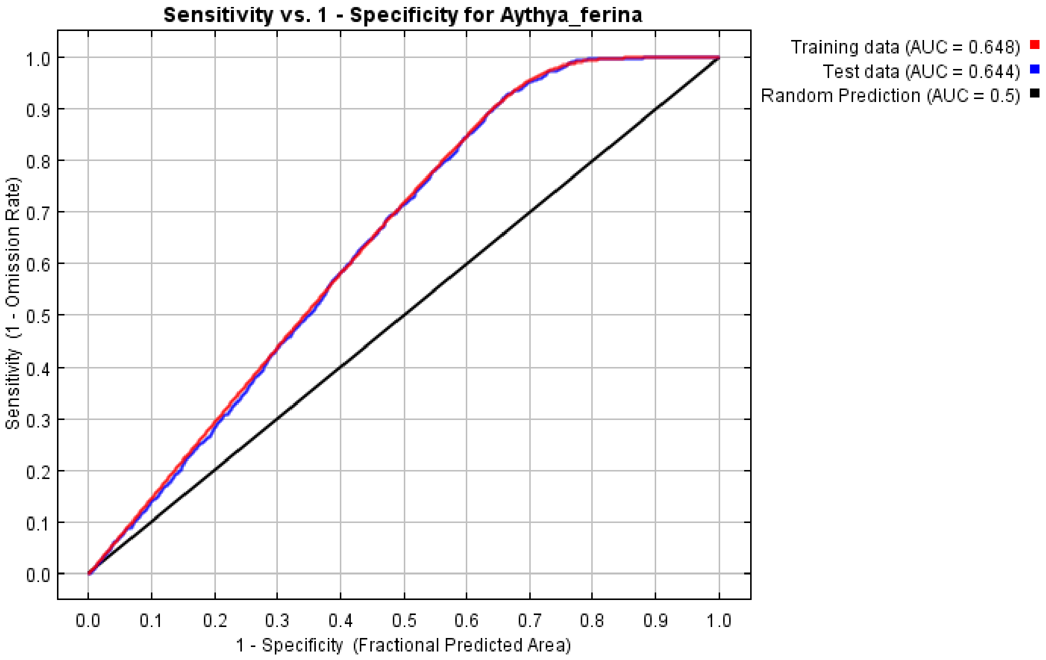


Figure S15: AUC plot for Aythya ferina winter season

Jackknife

Looking at the most relevant variables affecting the changes in suitability conditions for *Aythya ferina* in winter the Jackknife test (Fig. S16) of regularised training gain returns that bio_7 is reported to be the variable impacting the most, while the least useful information is bio_2 (Mean Diurnal Range). Other significant variable are bio_11 (mean diurnal precipitation) and bio_6 (mean temperature of coldest months). On the other hand, none of the environmental variables used contain really useful information that is not included in other variables but, the one decreasing the gain the most when it is omitted is bio_16 (precipitation of wettest quarter).

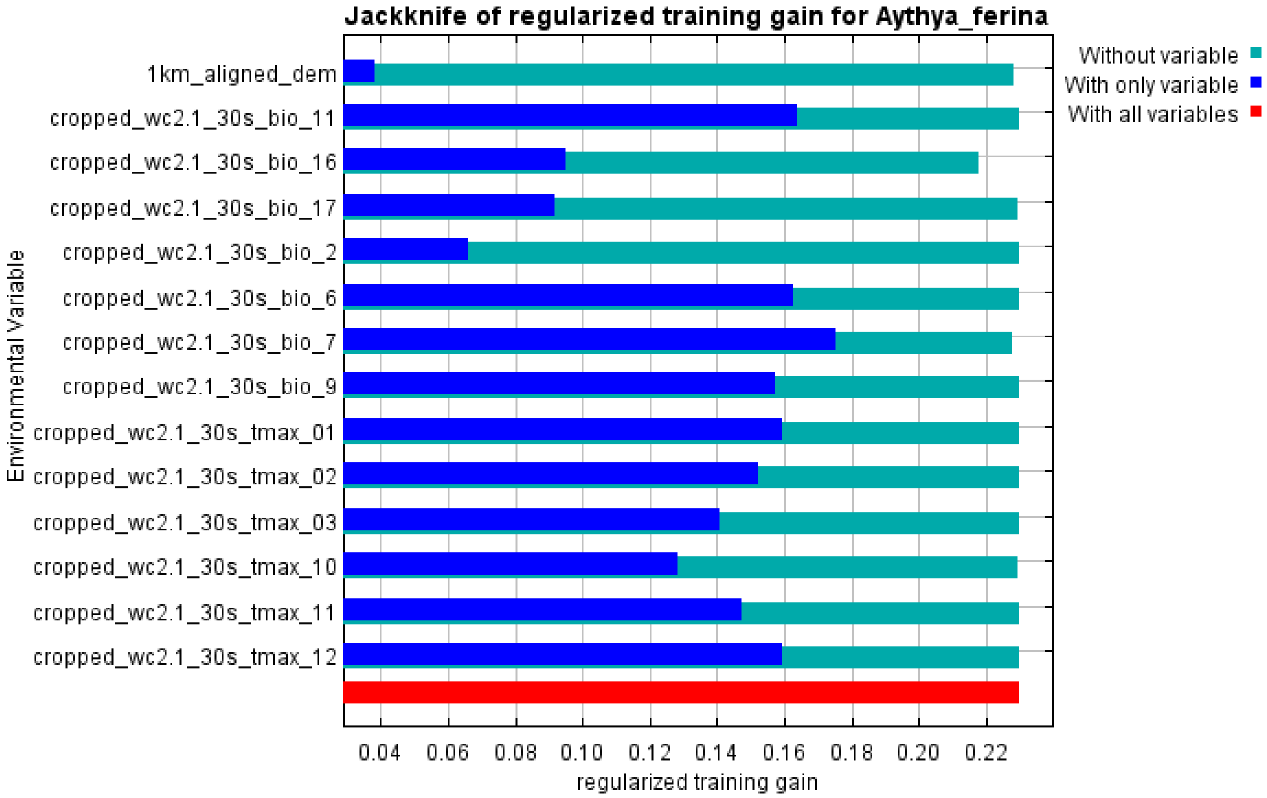


Figure S16: Jackknife of regularized training gain for Aythya ferina winter

Model for Aythya fuligula

Summer:

AUC

The AUC plot (Fig. S17) shows that the model used performs better than a random model would, given the AUC value of 0.599, for summer season of *Aythya fuligula* species.

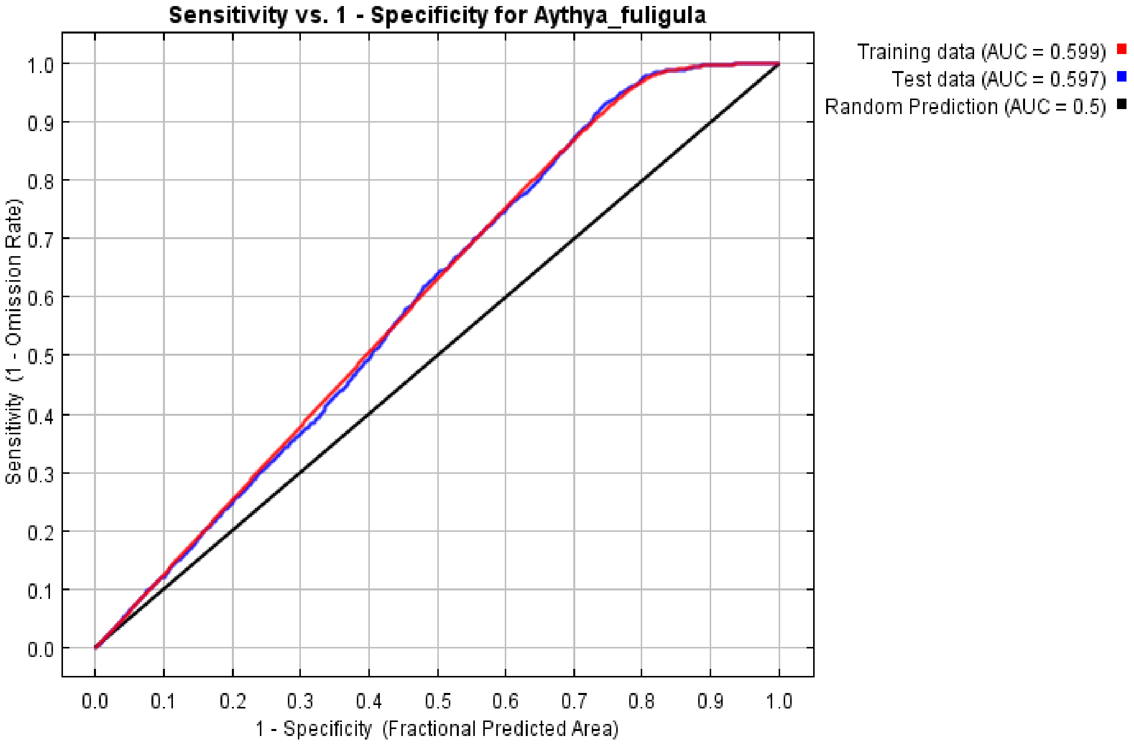


Figure S17: AUC plot for Aythya fuligula summer season

Jackknife

From the jackknife of regularized training gain for *Aythya fuligula* summer season (Fig. S18) it can be observed the most relevant variable which affects the changes in suitability conditions is bio_17 (precipitation of driest quarter). It is followed by bio_2 (mean diurnal range) and bio_9 (mean temperature of the driest quarter). Looking at light blue lines, none of them seems to contain very useful information not included in others; the one decreasing the most when omitted is bio_7 (temperature annual range).

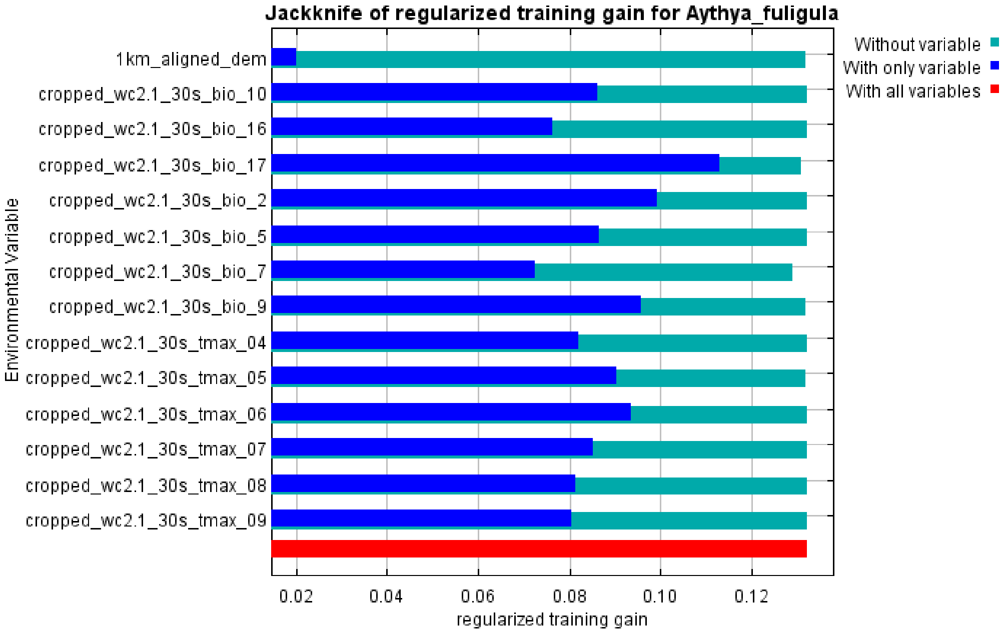


Figure S18: Jackknife of regularized training gain for Aythya fuligula summer

Winter:

AUC

The AUC plot (Fig. S19) shows that the model used performs better than a random model would, given the AUC value of 0.605, for winter season of *Aythya fuligola* species. It, therefore, performs slightly better than the case of summer season.

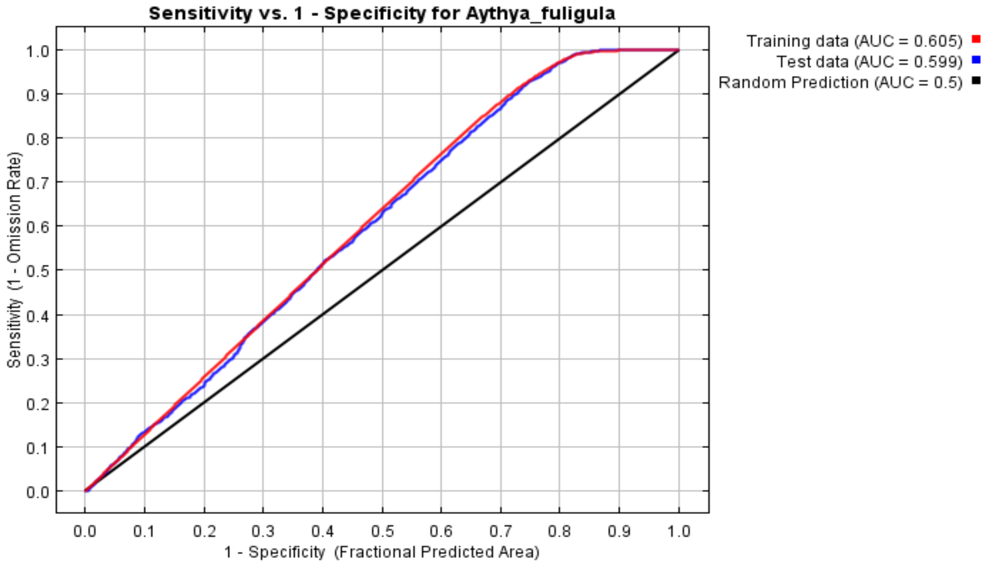


Figure S19: AUC plot for Aythya fuligula winter season

Jackknife

In *Figure S20* it is shown the jackknife plot for Aythya fuligola winter season. The most relevant variable which affects the changes in suitability conditions is bio_7 (temperature annual range, given by the difference between bio_5 and bio_6), followed by bio_9 (mean temperature of driest quarter). On the other hand, the variable which seems to contain the most useful information, given the decrease of the light blue line, is bio_16 (precipitation of wettest quarter).

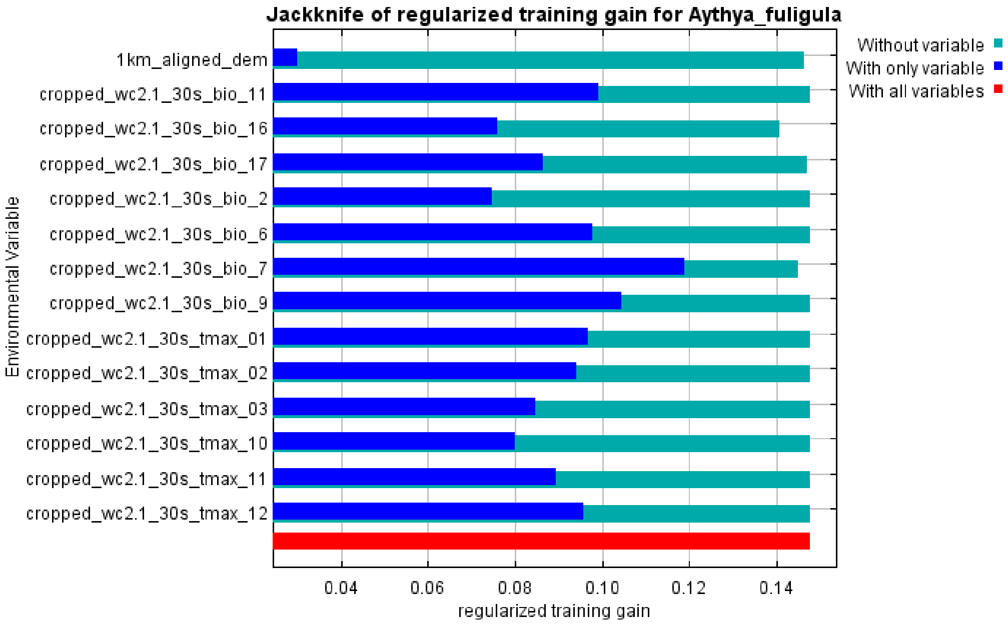


Figure S20: Jackknife of regularized training gain for Aythya fuligola winter

Model for Mareca Penelope

Summer:

AUC

The AUC plot (Fig. S21) shows that the model used performs very well compared to what a random model would do, given the AUC value of 0.868, for summer season of *Mareca penelope* species. This value is one of the highest among the species of this study.

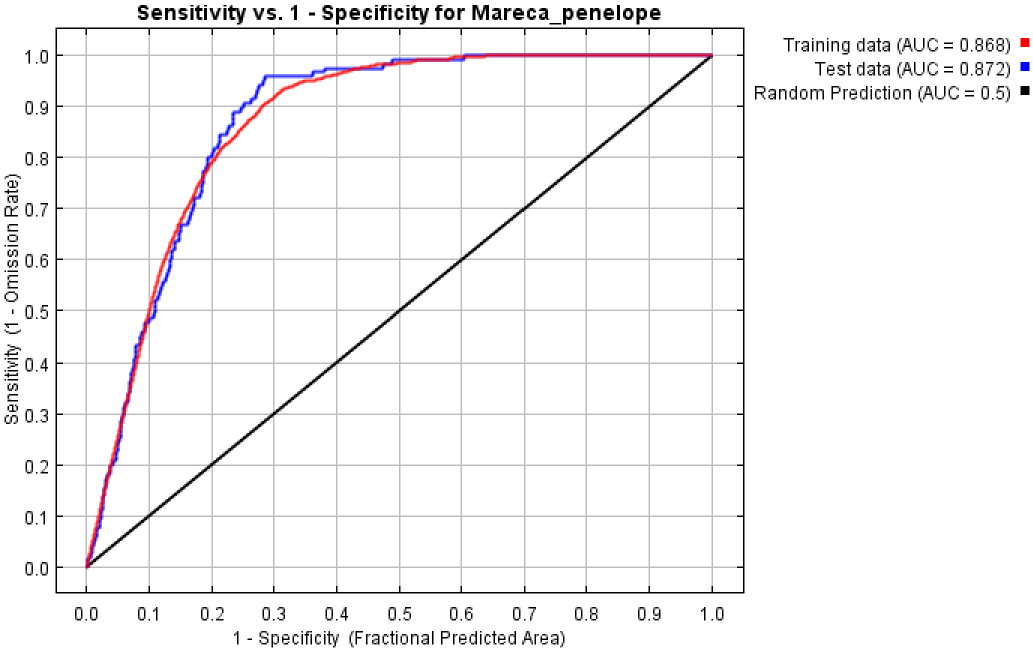


Figure S21: AUC plot for Mareca penelope summer season

Jackknife

The jackknife test outcomes for the most relevant bioclimatic and environmental variables (Fig. S22) report that bio_17 (precipitation of driest quarter) is the one impacting the most. Comparing this plot with the two other jackknife, other two relevant variables are predicted to be tmax_05 (May) and tmax_06 (June).

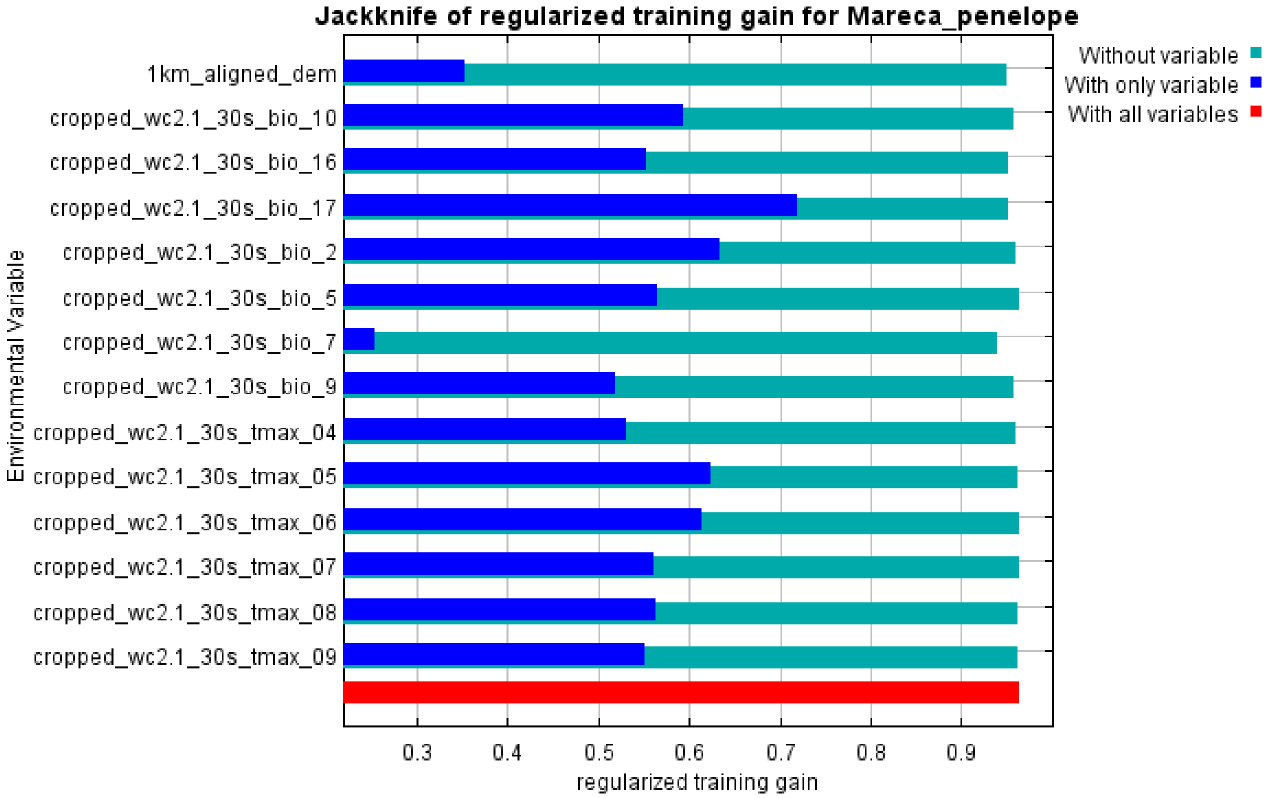


Figure S22: Jackknife of regularized training gain for Mareca penelope summer

Winter:

AUC

The AUC plot (Fig. S23) shows that the model used performs very well compared to what a random model would do, given the AUC value of 0.838, for winter season of *Mareca penelope* species. This value is one of the highest among the species of this study, and it is consistent with the extremely high value of AUC for summer season too.

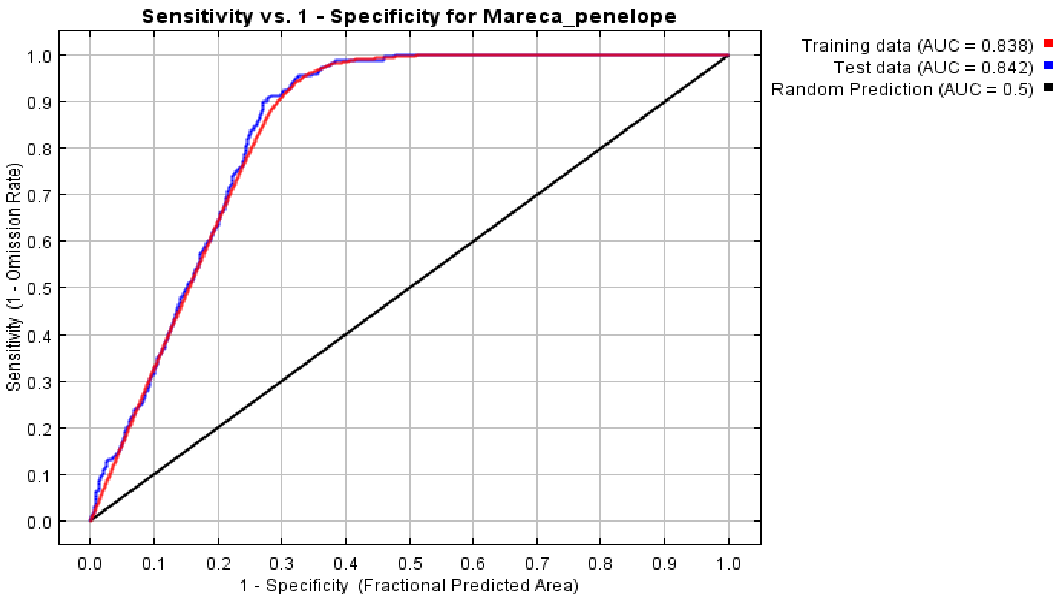


Figure S23: AUC plot for Mareca penelope winter season

Jackknife

Looking at *Figure S24*, the Jackknife of regularised training gain for *Mareca penelope* in winter seasons it seems that the variable affecting the most the change in suitable conditions is bio_17 (precipitation of the driest quarter). Moreover, comparing the results of the two others jackknife plots, another relevant variable is bio_11 (mean temperature of coldest quarter).

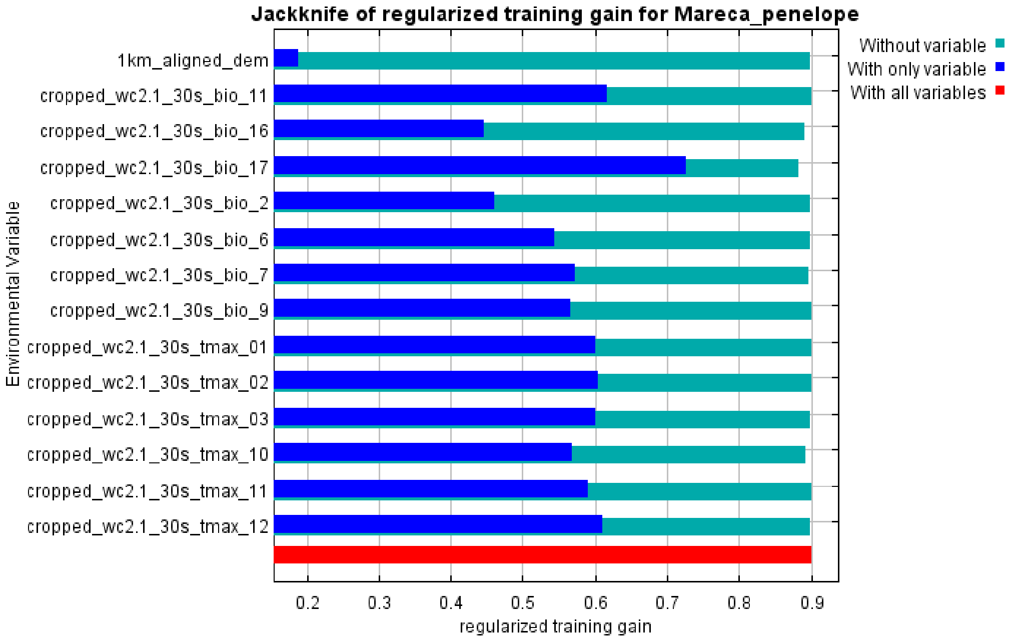


Figure S24: Jackknife of regularized training gain for Mareca penelope winter

Model for Mareca strepera

Summer:

AUC

The AUC plot (Fig. S25) shows that the model used performs very well compared to what a random model would do, given the AUC value of 0.867, for summer season of *Mareca strepera* species. This value is one of the highest among the species of this study.

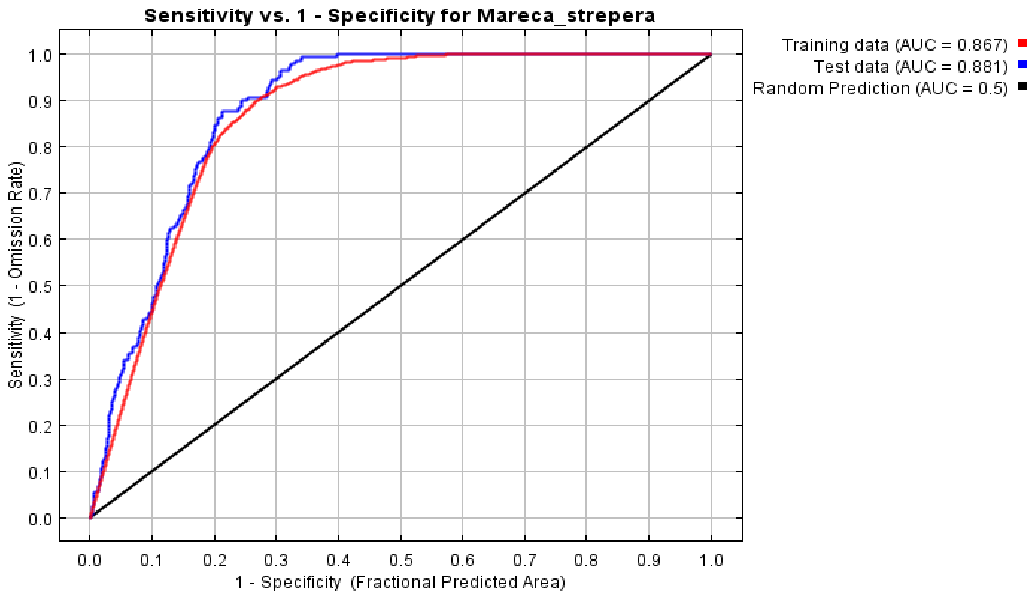


Figure S25: AUC plot for Mareca strepera summer season

Jackknife

In the following picture (Fig. S26) it is shown the output of the jackknife test for *Mareca strepera* summer season. The variables that seem to change the most the suitability condition predicted are bio_17 (precipitation of driest quarter) and bio_10 (mean temperature of warmest quarter). Moreover, looking also at the output of the two other jackknife plots, tmax_09 (September) seems to be among the most relevant variables considered. As it concerns the variable containing the most amount of information, it seems that none of the analysed contains information not covered by all the others; indeed, there is no relevant shorter light blue line.

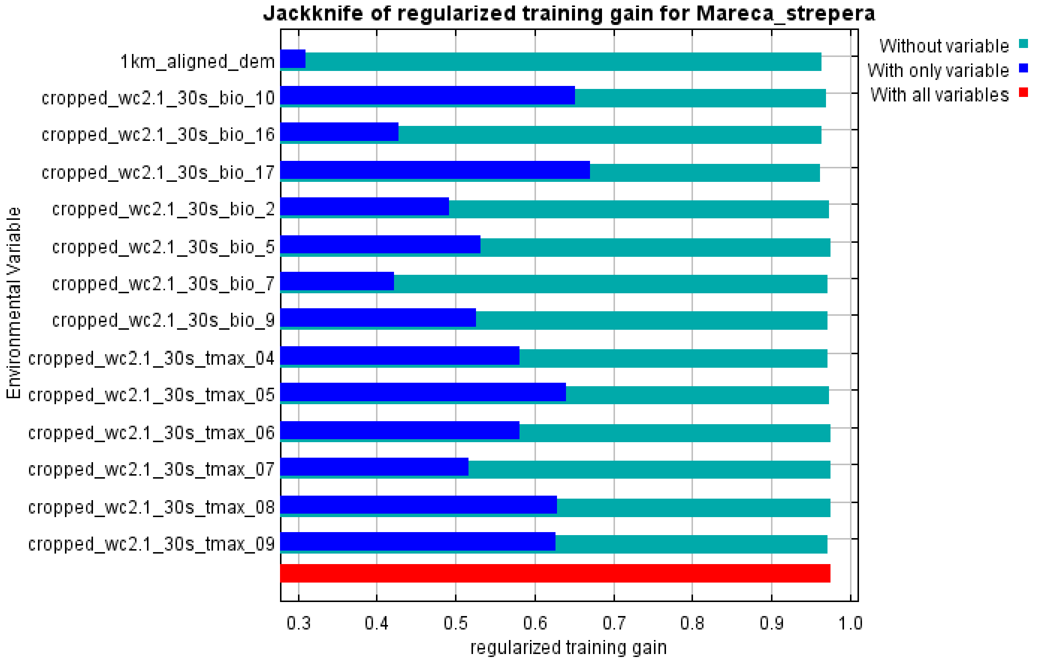


Figure S26: Jackknife of regularized training gain for Mareca strepera summer

Winter:

AUC

The AUC plot (Fig. S27) shows that the model used performs very well compared to what a random model would do, given the AUC value of 0.843, for winter season of *Mareca 97enelope* species. This value is one of the highest among the species of this study, and it is consistent with the extremely high value of AUC for summer season too.

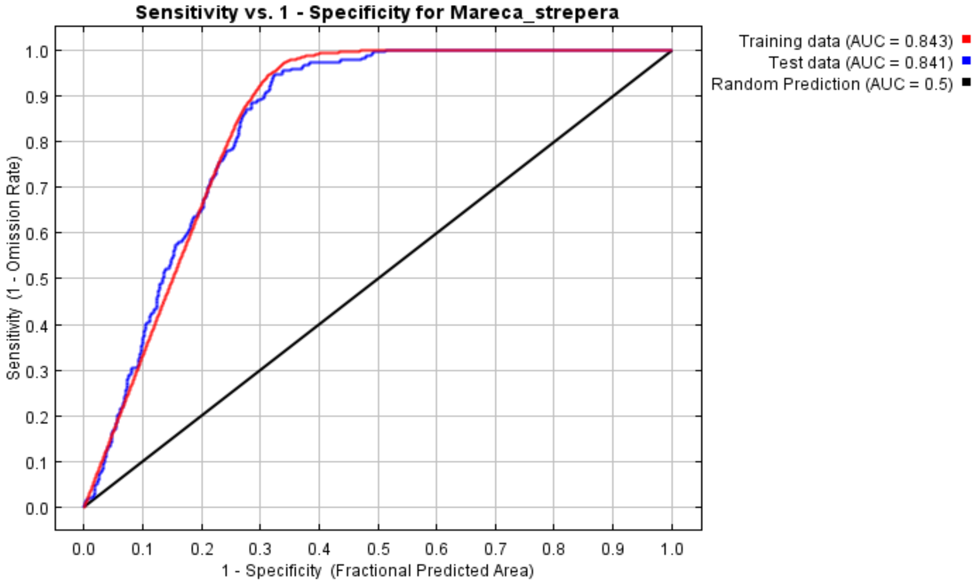


Figure S27: AUC plot for Mareca strepera winter season

Jackknife

The jackknife plot (Fig. S28) for *Mareca strepera* winter season predict that the most important variables affecting the suitability of this species are bio_17 (precipitation of driest quarter) and bio_11 (mean temperature of coldest quarter). Among all, bio_17 bioclimatic variable seems to be also the one containing the most information, even if the corresponding light blue line is not that much shorter than the others.

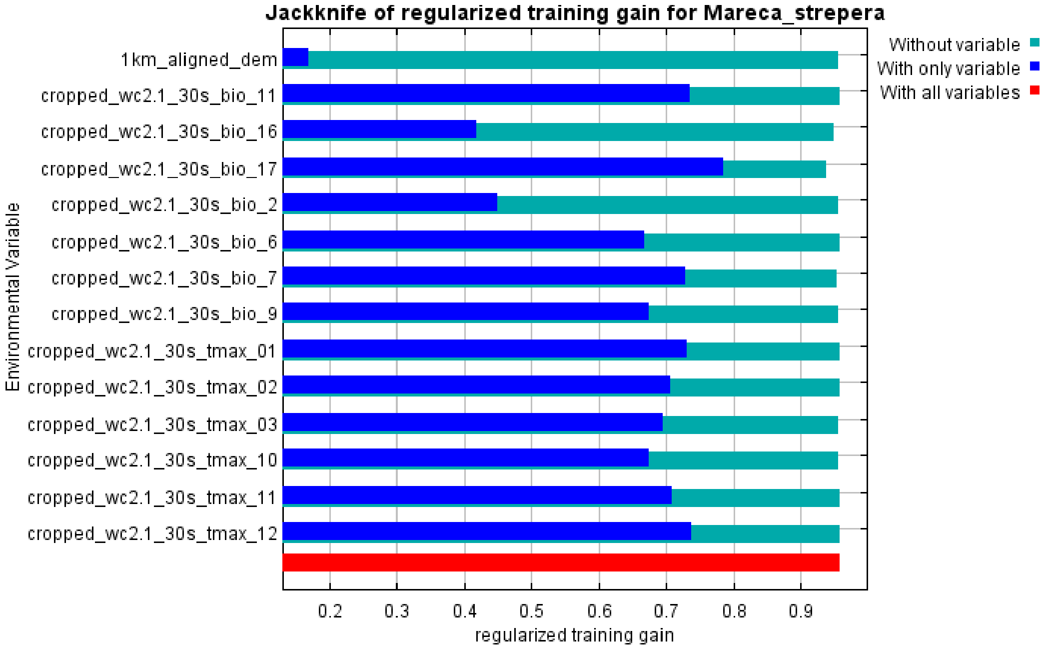


Figure S28: Jackknife of regularized training gain for Mareca strepera winter

Model for Spatula clypeata

Summer:

AUC

The AUC plot (Fig. S29) shows that the model used performs very well compared to what a random model would do, given the AUC value of 0.846, for summer season of *Spatula clypeata* species. This value is one of the highest among the species of this study.

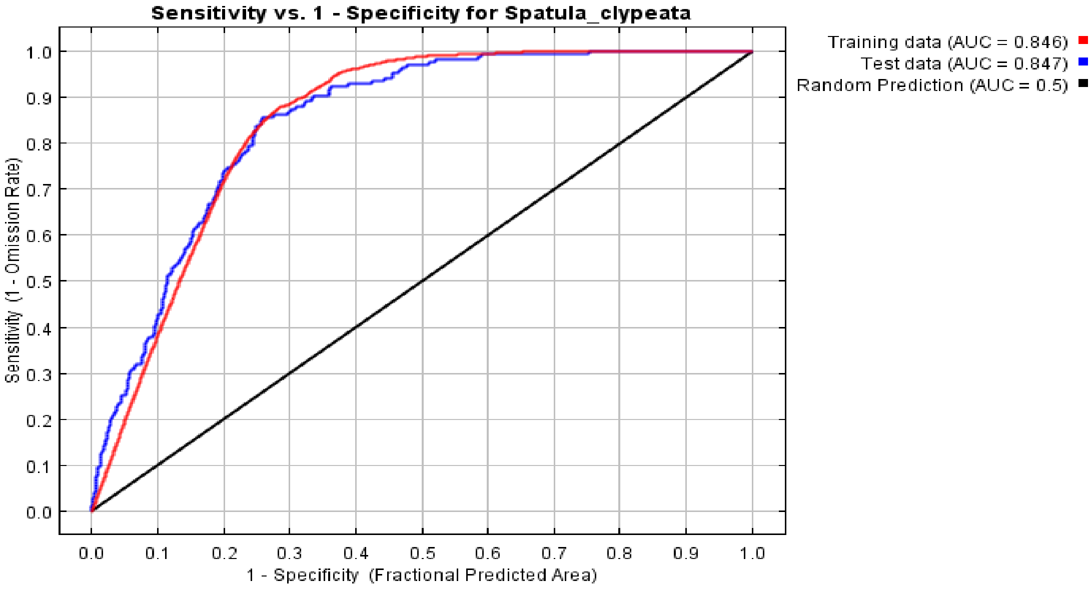


Figure S29: AUC plot for Spatula clypeata summer season

Jackknife

According to the jackknife plot (Fig. S30), the most important variable among the chosen to determine the suitability of a territory for *Spatula clypeata* is bio_17 (precipitation of driest quarter). Other relevant variables are predicted to be bio_10 (mean temperature of warmest quarter) and tmax_05 (May).

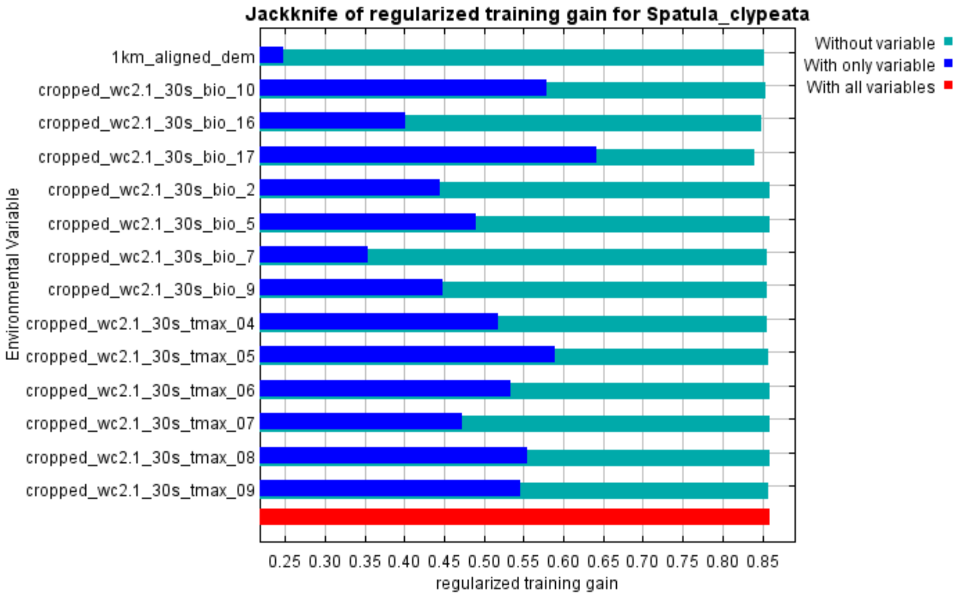


Figure S30: Jackknife of regularized training gain for Spatula clypeata summer

Winter:

AUC

The AUC plot (Fig. S31) shows that the model used performs very well compared to what a random model would do, given the AUC value of 0.846, for winter season of *Spatula clypeata* species. This value is one of the highest among the species of this study, and it is consistent with the extremely high value of AUC for summer season too.

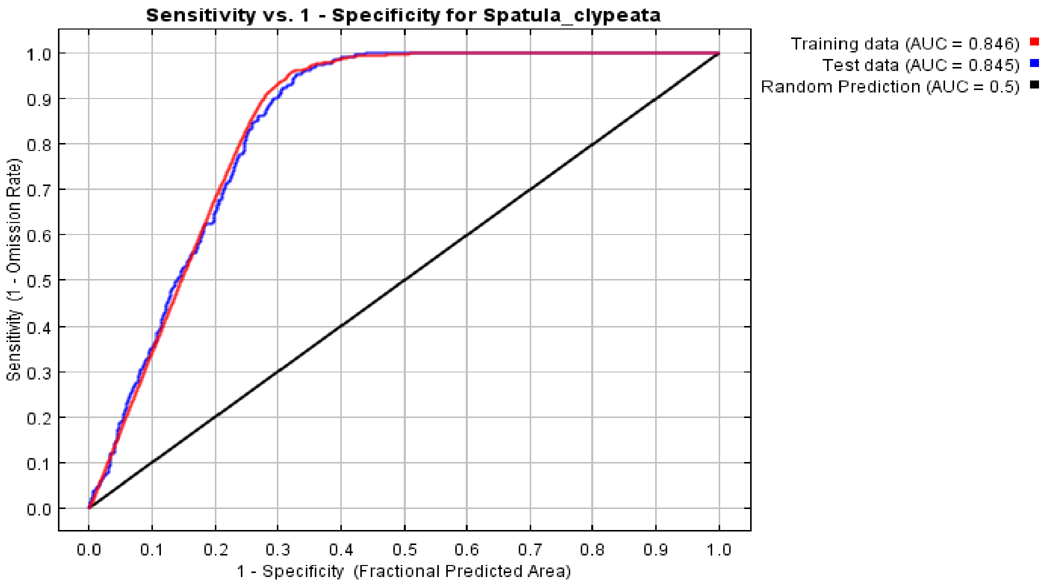


Figure S31: AUC plot for Spatula clypeata winter season

Jackknife

The jackknife plot of regularised training gain for *Spatula clypeata* for winter season (Fig. S32) shows that the predicted most important variables that determine the suitability of a region are bio_17 (precipitation of driest quarter), and the tmax for December and January (this is closely related to the importance that bio_11 has too, which represents the mean temperature of coldest quarter).

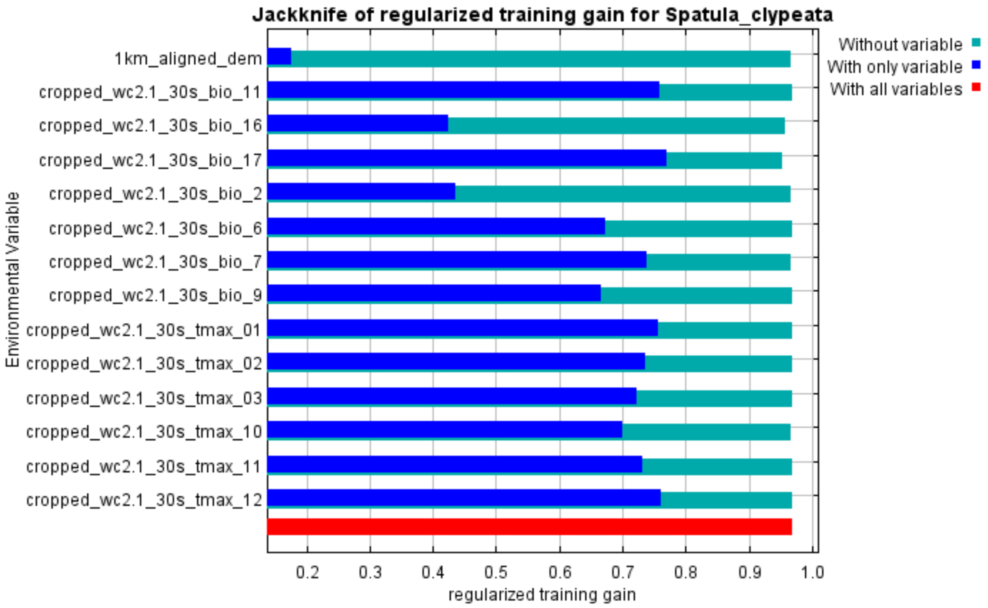


Figure S32: Jackknife of regularized training gain for Spatula clypeata winter

Model for Spatula querquedula

Summer:

AUC

The AUC plot (Fig. S33) shows that the model used performs very well compared to what a random model would do, given the AUC value of 0.857, for summer season of *Spatula querquedula* species. This value is one of the highest among the species of this study.

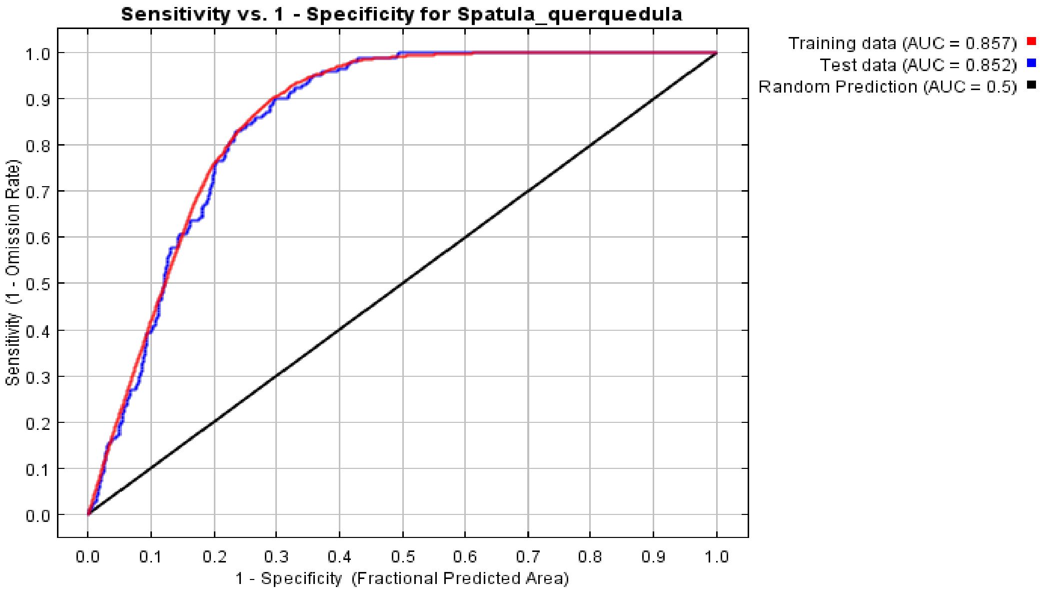


Figure S33: AUC plot for Spatula querquedula summer season

Jackknife

In *Figure S34* it is shown the jackknife plot of regularised training gain. The resulting outcome predicts that the most important variable affecting the suitability for this species is bio_17 (precipitation of driest quarter).

Comparing this plot with the other two jackknife Maxent outputs two more variables are predicted to have a relevant role: bio_10 (mean temperature of warmest quarter), and tmax5 and tmax9 (corresponding to months of May and September). The variable which seems to contain the most amount of information is bio_17 itself.

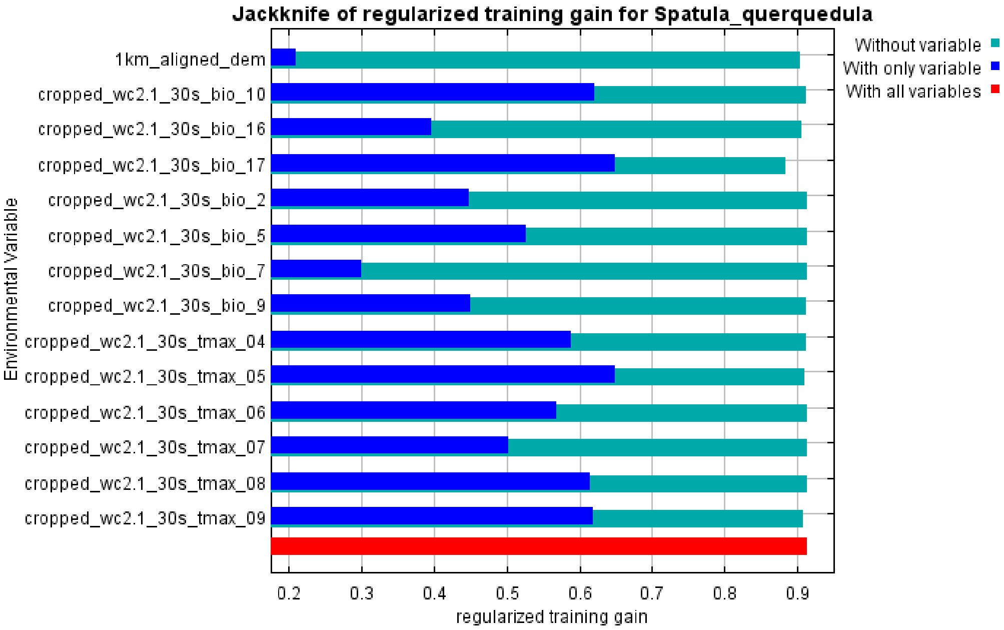


Figure S34: Jackknife of regularized training gain for Spatula querquedula summer

Winter:

AUC

The AUC plot (Fig. S35) shows that the model used performs very well compared to what a random model would do, given the AUC value of 0.921, for winter season of *Spatula querquedula* species. This value is the highest among the species of this study, and it is consistent with the extremely high value of AUC for summer season too.

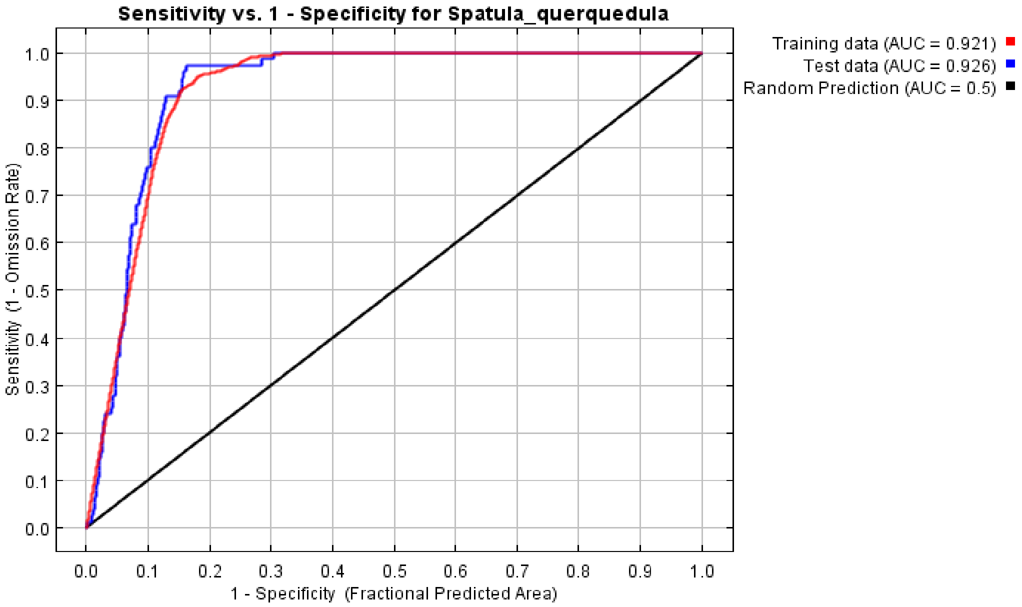


Figure S35: AUC plot for Spatula querquedula winter season

Jackknife

According to the jackknife plot (Fig. S36), the most important variable is predicted to be bio_17 (precipitation of driest quarter). Moreover, by observing the other two output jackknife plot, other relevant bioclimatic variables seem to be bio_7 (temperature annual range) and bio_11 (mean temperature of coldest quarter). None of the considered variables seem to contain information other variables don't present; nevertheless, the shortest light blue line corresponds to bio_17, therefore, when omitted, the model loses some relevant pieces of information.

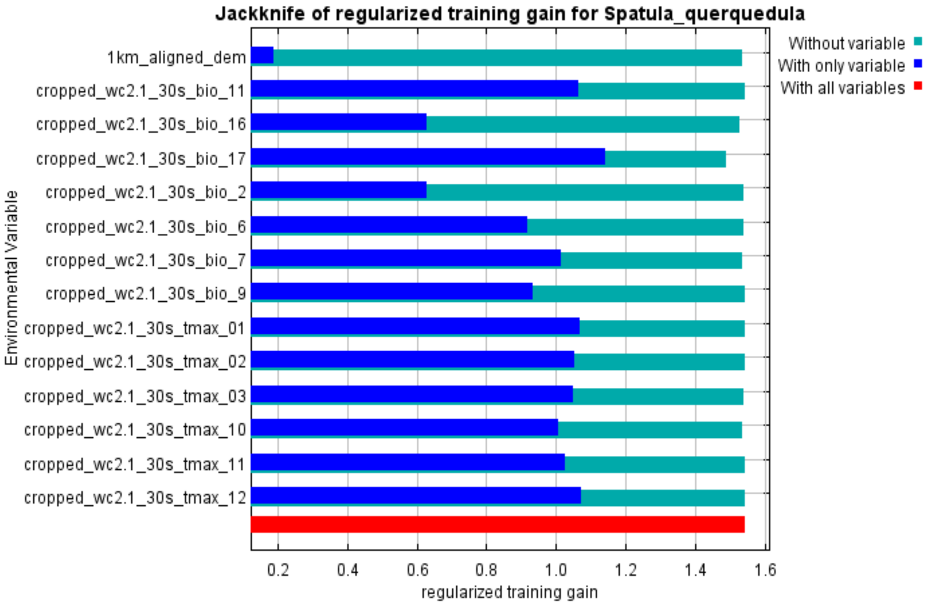


Figure S36: Jackknife of regularized training gain for Spatula querquedula winter