Climate Change Induced Habitat Contraction in Critically Endangered European Eel Habitat: A Species Distribution Model Analysis

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Abstract

The European Eel, *Anguilla anguilla,* is critically endangered due to overexploitation, habitat loss, and climate change. This study aims to model the species' habitat suitability under current and future climate scenarios to guide conservation efforts. Using a species distribution model (SDM) with occurrence records (n = 7,869) from the Global Biodiversity Information Facility and environmental variables from the WorldClim database (19 bioclimatic variables) alongside an extensive literature review, we effectively determine habitat suitability and the impact of climate change on the species. The SDM showed a high predictive performance with an AUC value of 0.981, and the modeling determined that significant predictors of suitability included various temperature and precipitation variables, highlighting the European Eel's sensitivity to climatic conditions. Results further indicate a considerable reduction in suitable habitats under future climate scenarios, with notable contractions in current habitable areas. Future projections identify potential refuge areas with less climate impact, which is crucial for targeted conservation efforts. The findings underscore the urgency of implementing adaptive conservation strategies to mitigate climate change impacts on *A. Anguilla*. The study provides a scientific basis for habitat protection and policy development to ensure the species' long-term survival.

Introduction

The European Freshwater Eel, *Anguilla anguilla* (Linnaeus, 1758)*,* is a migratory fish species belonging to the Anguilldae family (Pike *et al*., 2020). In 2007, the European Eel was listed in Appendix II of the Convention on International Trade in Endangered Species (Barcala *et al*., 2022). The same year, the International Union for Conservation of Nature (IUCN) classified the species as critically endangered (Cardas *et al*., 2020).

The European eel has a complex life cycle. The species spawns in a panmictic manner in the Sargasso Sea and, throughout its life, lives primarily in European and North African inland waters (Bracamonte *et al*., 2015, p. 858). Further, the eel's life cycle has five principal phases: the leptocephalus, glass eel, elver, yellow eel, and silver eel stages (Arai *et al*., 2006). The eels begin as larvae (leptocephali) drifting on the Gulf Stream and are transported by the North Atlantic Current across the Atlantic Ocean. After metamorphosing into glass eels, they leave oceanic currents and tend to migrate upstream in their elver stage, which occurs six to eight months after hatching. The eels then develop during their yellow stage in freshwater habitats of Europe and North Africa. Finally, at varying ages, the yellow eels metamorphose into silver eels, eventually migrating downstream to the ocean to spawn offspring in the Sargasso Sea (Arai *et al*., 2006).

The population has consistently declined since the 1980s throughout its area of distribution. This decline has occurred to such an extent that the stocks are now upwards of ten times lower than they were decades ago (Feunteun, 2002). The stocks of the species have drastically decreased due to various factors, including overexploitation, illegal trade, and habitat loss (Cardas *et al*., 2020). Furthermore, Gulf Stream shifts impact the survivability of *leptocephali* larvae during their transoceanic migration (Feunteun, 2002). Additionally, introducing the invasive swim bladder nematode *Anguillicola crassus*, a parasitic worm frequently spreading throughout eel populations, has led to the stock's decline. The parasite was introduced to Europe from Southeast Asia in the early 1980s and, within ten years, had infested itself in the entirety of the eel's distribution range. Moreover, it has reached 60-70% prevalence within eel populations, which has caused widespread impairment to the eel's swim bladder functioning, reduced swimming ability, and has likely impacted spawning migration (Bracamonte *et al*., 2015). While these parasites are present, they are not the sole cause of population decline. Environmental factors, like some of those mentioned previously, have played a devastating role. For instance, research has concluded that the survival of eel larvae has a strong correlation with food availability, and over the last four decades, changes in marine production due to climate change have had a significant impact. Furthermore, shifts in oceanic temperatures initially detected in the late 1970s play a role in population decline (Bonhommeau *et al*., 2023).

Despite the European eel's critical status, no comprehensive study has addressed its habitat suitability and potential distribution using species distribution models (SDM). To fill this gap, we aim to develop an SDM for *A. Anguilla* that will highlight possible environmental factors influencing species distribution, predict current habitat distribution by utilizing existing occurrence records, and project future changes in habitat suitability under specific climate change scenarios. The methodology integrates species-occurrence data from recent fieldwork and extensive literature review, coupled with environmental predictors. This approach will enable us to map the potential shifts in suitable habitats for *A. Anguilla* and identify critical areas for conservation efforts. Finally, we will evaluate the threats to the European Eel population and outline strategies to ensure the species' long-term survival. The implications of this research are significant for conservation planning and policy development, providing a scientific basis for targeted habitat protection and restoration. We hypothesize that climate change will reduce suitable habitats for *A. Anguilla* due to the numerous previously mentioned factors. Significant temperature variations will strongly correlate and negatively impact the species' future distribution area.

Methods

Data Collections

We obtained occurrence records of *A. anguilla* from the Global Biodiversity Information Facility (GBIF, 2024). The GBIF is a database and data infrastructure supported by multiple national governments, aimed at providing open-access biodiversity data for the public and the science community. The total number of occurrences for European Eel downloaded is 736,713. These occurrences are found mainly in Western Europe, most prominently in Great Britain, France, and Spain. The timeline of the sightings for this species ranges from 1580 to 2024. We filtered to keep only occurrences with coordinates. The latitudes range from 36 to 63, and longitudes range from -29 to 15.

Environmental Variables

We acquired environmental variables representing the current climatic conditions from the WorldClim database (Fick and Hijmans, 2017) at a resolution of 2.5 arc min. The environmental variables included: Bio1 = Annual mean temperature, Bio2 = Mean diurnal range (max temp – min temp) (monthly average), Bio3 = Isothermality (Bio1/Bio7) * 100, Bio4 = Temperature Seasonality (Coefficient of Variation), Bio5 = Max Temperature of Warmest Period, Bio6 = Min Temperature of Coldest Period, Bio7 = Temperature Annual Range (Bio5-Bio6), Bio8 = Mean Temperature of Wettest Quarter, Bio9 = Mean Temperature of Driest Quarter, Bio10 = Mean Temperature of Warmest Quarter, Bio11 = Mean Temperature of Coldest Quarter, Bio12 = Annual Precipitation, Bio13 = Precipitation of Wettest Period, Bio14 = Precipitation of Driest Period, Bio15 = Precipitation Seasonality (Coefficient of Variation), Bio16 = Precipitation of Wettest Quarter, Bio17 = Precipitation of Driest Quarter, Bio18 = Precipitation of Warmest Quarter, and Bio19 = Precipitation of Coldest Quarter. Using R software (R Core Team, 2023) and a raster package (Hijmans, 2024), we trimmed the environmental variables so that the geographic range of environmental variables was contained with 30-degree latitudes and 15-degree longitudes. The extent of the ecological variables covers and extends beyond the latitudinal and longitudinal ranges of *A. anguilla*.

In addition, to project species' future suitable areas, we acquired environmental variables representing future climatic conditions for 2061- 2080 under the model MPI-ESM1-2-HR and CMIP6 (Gutjahr *et al*., 2019). The future climatic raster layers were also trimmed using the abovementioned sampling extent.

Modeling Strategy

To investigate the suitable habitat areas of the European Eel, we performed a multivariate generalized linear model (GLM). We randomly selected 10,000 pseudo-absence, or "background" points, within the range of the environmental variables (see section above). The number of 10,000 pseudo-absence points followed the recommendation by Barbet-Massin *et al*. (2012). After running the GLM model, we converted the continuous probability of habitat suitability to a binary response output (suitable = TRUE or FALSE). The suitability cut-off was equal to the threshold at which the sum of the model sensitivity (true positive rate) and specificity (true negative rate) is highest (Field *et al.,* 1997; Liu *et al*., 2011). We then used five-fold cross-validation to evaluate the trained GLM; in each cross-validation, 80% of the occurrence data were training data, leaving the remaining 20% as testing data. We assessed the performance of GLM by calculating the Area Under the ROC Curve (AUC). We then projected future suitable habitat areas for *A. anguilla* in 2061-2080.

Results

The final GBIF dataset of *A. Anguilla* contains 7869 records with coordinates, forming a substantial basis for the species distribution model. The generalized linear model shows an AUC value of 0.981, indicating exceptional predictive performance and confirming the model's reliability in assessing habitat suitability for the European Eel (Figure 1). In analyzing the GLM model output, several bioclimatic variables showed significant correlations with habitat suitability. Variables including Bio1 (Annual mean temperature), Bio2 (Mean diurnal range), and Bio11 (Mean Temperature of Coldest Quarter) exhibited strong positive correlations with the presence of the European Eel. This indicates that the species prefers environments with moderate and stable temperatures. Conversely, variables including Bio3 (Isothermality) and Bio12 (Annual Precipitation) had significant negative correlations, suggesting that extreme weather conditions, high precipitation levels, and temperature variability may be detrimental to the species' habitat suitability. In total, bioclimatic factors 3, 5, 8, 9, 10, 12, 14, and 15 show a significant negative correlation to predicting species presence, and 1, 2, 4, 6, 7, 11, 13, 16, 17, 18, and 19 show a significant positive correlation to species presence (Table 1). The comparison between current and future suitable habitat areas reveals a notable contraction in the European Eel's habitat under projected climate scenarios (Figure 2).

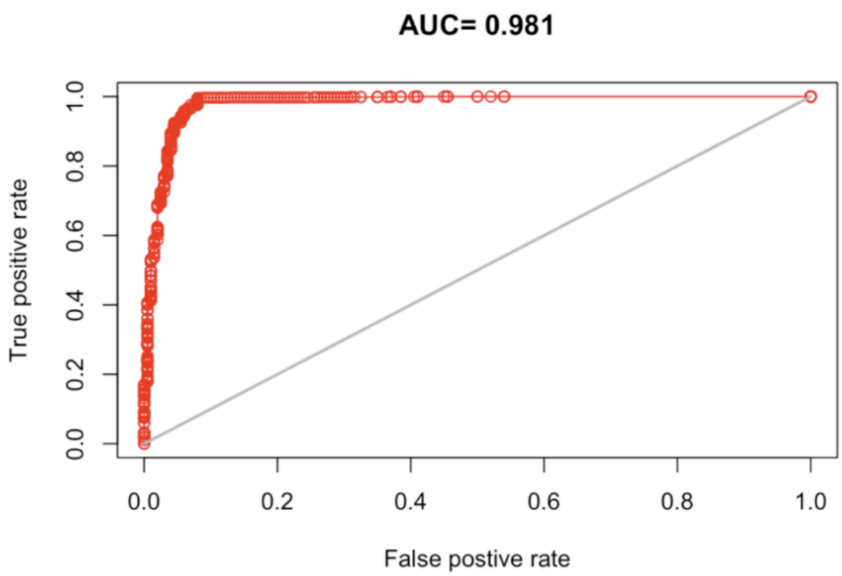

Figure 1: Depiction of AUC Value

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	1.581070e+02	2.003557e+01	7.89131704	2.990140e-15
wc2.1_2.5m_bio_1	2.560142e+01	2.271401e+00	11.27120197	1.820673e-29
wc2.1_2.5m_bio_2	1.578707e+01	2.595615e+00	6.08220804	1.185386e-09
wc2.1_2.5m_bio_3	-4.438393e+00	5.755603e-01	-7.71142969	1.244160e-14
wc2.1_2.5m_bio_4	3.498738e-01	9.556178e-02	3.66123102	2.510063e-04
wc2.1_2.5m_bio_5	-7.126875e+05	1.856710e+05	-3.83844314	1.238169e-04
wc2.1_2.5m_bio_6	7.126870e+05	1.856709e+05	3.83844121	1.238178e-04
wc2.1_2.5m_bio_7	7.126826e+05	1.856708e+05	3.83841987	1.238286e-04
wc2.1_2.5m_bio_8	-2.364519e-02	3.779037e-02	-0.62569347	5.315160e-01
wc2.1_2.5m_bio_9	-4.994282e-01	1.061450e-01	-4.70515245	2.536763e-06
wc2.1_2.5m_bio_10	-2.829496e+01	4.001964e+00	-7.07026803	1.546347e-12
wc2.1_2.5m_bio_11	7.545191e+00	3.674910e+00	2.05316354	4.005672e-02
wc2.1_2.5m_bio_12	-5.546660e-02	1.008709e-02	-5.49877352	3.824420e-08
wc2.1_2.5m_bio_13	6.188167e-02	6.181002e-02	1.00115916	3.167499e-01
wc2.1_2.5m_bio_14	-8.523509e-01	9.066684e-02	-9.40091160	5.409236e-21
wc2.1_2.5m_bio_15	-5.199755e-01	1.364315e-01	-3.81125670	1.382621e-04
wc2.1_2.5m_bio_16	2.232976e-03	3.414557e-02	0.06539577	9.478589e-01
wc2.1_2.5m_bio_17	2.197681e-01	3.716125e-02	5.91390502	3.340906e-09
wc2.1_2.5m_bio_18	1.352759e-01	1.313743e-02	10.29697973	7.270832e-25
wc2.1_2.5m_bio_19	7.549080e-02	1.462055e-02	5.16333510	2.425883e-07

Table 1: Bioclimatic Variable Impact on the Determination of Habitat Suitability

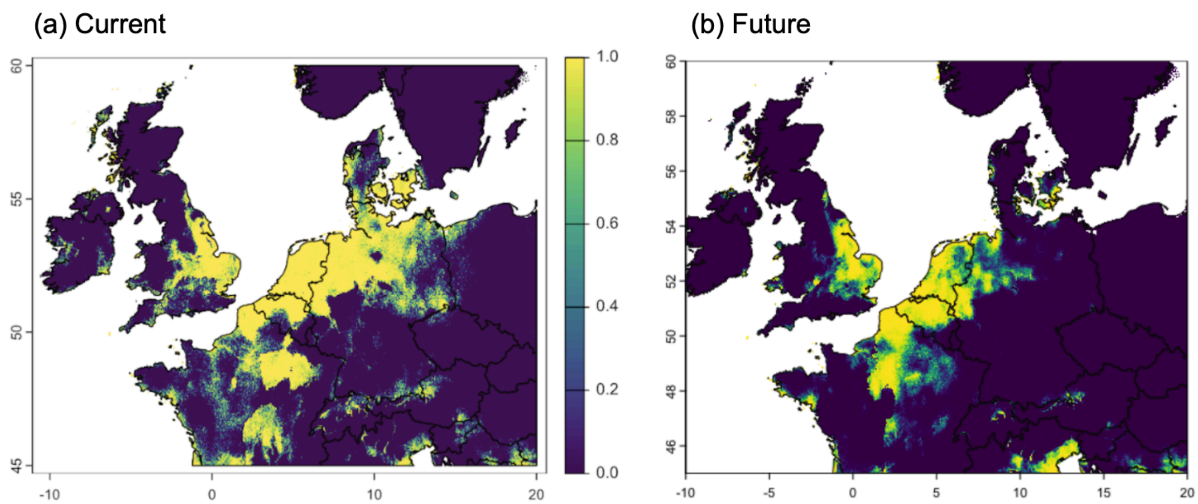

Figure 2: Depiction of (a) Current Suitable Habitat Environments and (b) Future Suitable Habitat Environments for *A. Anguilla*

Discussion

Results Interpretation

The results from our species distribution model (SDM) for the European Eel support the hypothesis that climate change will reduce suitable habitats for this species. The model's high AUC value of 0.981 indicates a strong predictive performance, underscoring the robustness and reliability of the SDM. The environmental variables identified as significant habitat suitability predictors, including positively and negatively correlated bioclimatic factors, highlight the complex interplay between the eel's presence and climatic conditions. The substantial dataset obtained from the Global Biodiversity Information Facility (GBIF), comprising 7,869 records with coordinates, provided a comprehensive basis for the analysis. Despite potential issues with pseudo-replication and some missing data, the model's thorough cross-validation and extensive temporal and spatial scope ensured a high degree of reliability. The multiple predictions tested and the independent lines of evidence from various bioclimatic factors further validated the model's findings, supporting the original hypothesis.

Despite the high-quality data and model validation, potential issues such as incomplete data coverage and the limitations of SDM may influence the results. SDM cannot take into account, for instance, food availability, which literature has pointed to as an essential factor of survival in young eel populations. Nevertheless, the model's cross-validation with the inclusion of multiple bioclimatic factors helps to mitigate potential concerns. The results align with the hypothesis that climate change and variable temperature significantly impact habitat suitability for *A. Anguilla*.

Explanation for Observed Patterns

The ecological requirements of the European Eel can explain the observed patterns in species occurrence and specific climate variables. Positive relationships between species occurrence and variables such as Bio1 (Annual mean temperature) and Bio11 (Mean

Temperature of Coldest Quarter), as well as those listed in the result section, suggest that the eel thrives in stable, moderate climates with adequate temperature ranges. Conversely, negative relationships with variables like Bio3 (Isothermality) and Bio12 (Annual Precipitation), alongside other negatively correlated variables listed in the results section, indicate that extreme variations in temperature and precipitation may be detrimental to eel populations. The expectation of shrinking suitable habitat areas under future climate scenarios aligns with predictions of increased temperature variability and altered precipitation patterns, which can disrupt the eel's complex life cycle (Vaughan *et al*., 2021). Range shifts are also anticipated, with eels potentially moving to higher latitudes or altitudes to find suitable habitats, driven by changes in temperature and precipitation that affect their breeding and feeding grounds.

Relating Findings to Broader Context

The general ecological concept examined here is the impact of climate change on habitat suitability and species distribution. This concept has been widely studied across various taxa and ecosystems, with many studies reporting similar patterns of habitat contraction and range shifts in response to changing climatic conditions. While the findings of this study are specific to the European Eel, they could be applied to other migratory aquatic species with similar life cycles and ecological requirements. Further research across different geographic regions and species is necessary to generalize these conclusions. The limitations of this research include potential biases in the GBIF dataset, such as uneven sampling effort and temporal gaps. Future studies could address these limitations by incorporating additional data sources and improving sampling methods. The findings of this research have significant implications for conservation and management decisions. Identifying and protecting critical habitats, especially those predicted to remain suitable under future climate scenarios, will be essential for the long-term survival of the European Eel (*Eel*, n.d.). These results also contribute to understanding the broader ecological issue of how climate change impacts species distributions and habitat suitability. By highlighting the specific bioclimatic factors influencing the eel's distribution, this study provides valuable insights for developing targeted conservation strategies to mitigate the effects of climate change on endangered species.

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