Understanding and predicting the global distribution patterns of the common carp (*Cyprinus carpio*) using species distribution models

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BACKGROUND AND AIMS

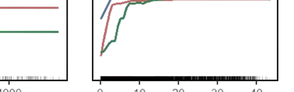
Cyprinus carpio is one of the world's most damaging invasive freshwater fish species. Native to Eurasia, it has spread globally through human-mediated introductions, aided by traits such as high fecundity and broad environmental tolerance. Its potential global invasion range has not yet been assessed using species distribution models (SDMs). Given that its establishment poses a serious threat to aquatic biodiversity and water quality worldwide, mapping their global distribution is fundamental for effective conservation and management.

1. **Predict the global distribution of *C. carpio* and determine the main environmental factors driving its spread.**
2. **Identify climatically and ecologically suitable areas for *C. carpio*.**

METHODS

RStudio

GBIF Global Biodiversity Information Facility



Variable	Abbreviation
Climate	
Max T of the warmest month	BIO5
Min T of the coldest month	BIO6
Mean annual precipitation	BIO12
Precipitation seasonality	BIO15
Topography	
Elevation	NA
Anthropic pressure	
Human footprint	NA

Model performance evaluated using Area Under the curve (AUC) and Person correlation coefficient (Cor).

General Linear Model (GLM)

Maximum Entropy (MaxEnt)

Random Forests (RF)

→ Ensemble model

Presence records obtained from GBIF and cleaned using *CoordinateCleaner*.

+

Selection of non-collinear climatic, topographic, and human footprint variables using VIF analysis.

→ SDMs with a 70/30 train-test split.

Partial dependence plots
Variable importance plots

→ AUC-Weighted ensemble model

Habitat suitability map

RESULTS

Predictive model	Performance metrics: AUC (± SE)	Performance metrics: Cor
GLM	0.9381 (± 0,0035)	0.7353
MaxEnt	0.9452 (± 0,0039)	0.7882
RF	0.9828 (± 0,0017)	0.7654
Ensemble	0.9793 (± 0,0020)	0.8155

Figure 1. Model performance metrics for the four predictive models, reporting the Area Under the Curve (AUC) and the Pearson correlation coefficient (Cor).

Figure 2. Partial dependence plots for the environmental variables, comparing the three modeling approaches. Rug plots along the x-axis indicate the density of observed data points.

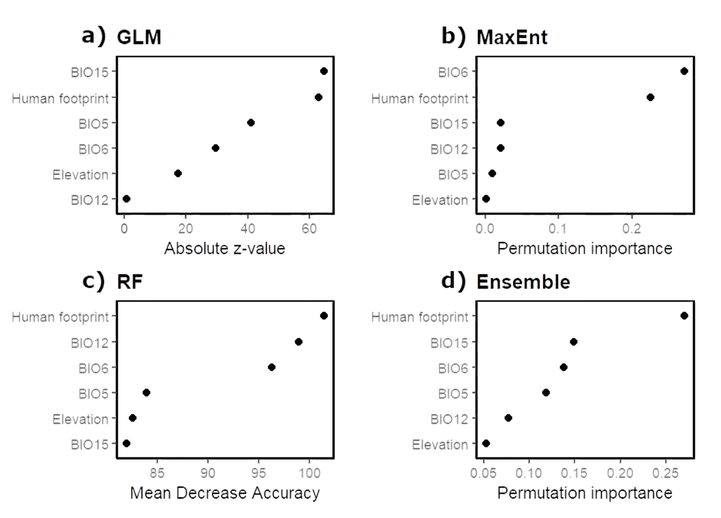


Figure 3. Relative importance plots. The x-axis shows the variable importance.

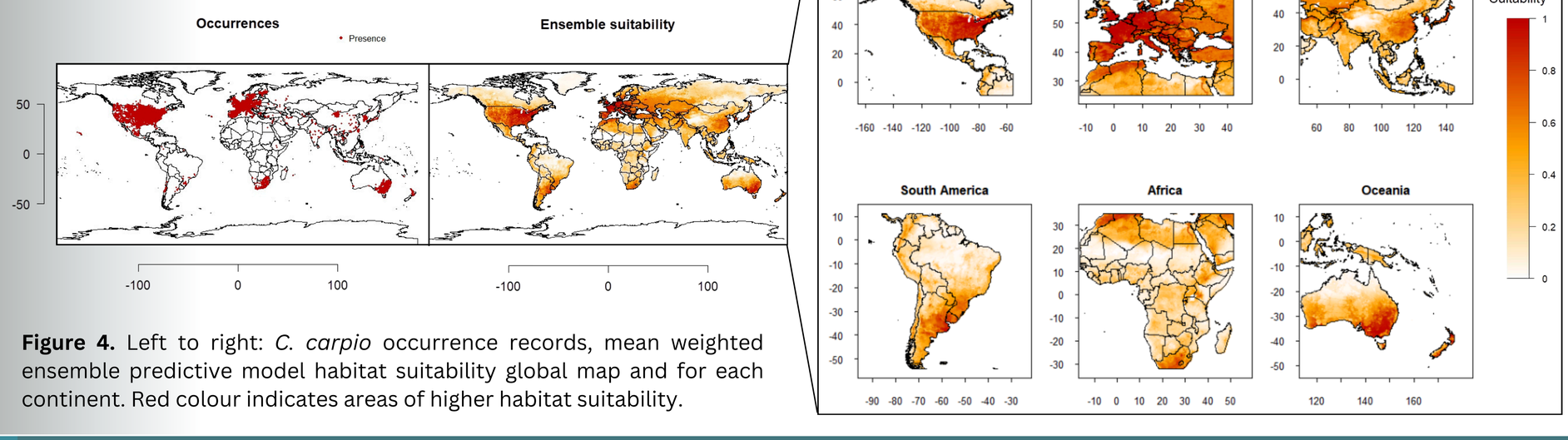


Figure 4. Left to right: *C. carpio* occurrence records, mean weighted ensemble predictive model habitat suitability global map and for each continent. Red colour indicates areas of higher habitat suitability.

MODEL PERFORMANCE

All models showed excellent predictive performance. RF achieved the highest AUC. However, the ensemble model showed the highest consistency and was selected for interpretation (**Fig. 1**).

KEY ENVIRONMENTAL VARIABLES

Suitability increased with warmer temperatures (BIO5), moderate winter temperatures (BIO6), moderate annual precipitation (BIO12) and high human footprint. It decreased with increasing precipitation seasonality (BIO15) and elevation (**Fig. 2**).

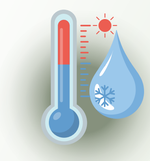
Human footprint was the most influential predictor in the ensemble model. Precipitation seasonality (BIO15), minimum temperature of the coldest month (BIO6) and maximum temperature of the warmest month (BIO5) were important variables too (**Fig. 3**).

HABITAT SUITABILITY PATTERNS

High suitability was predicted in North America, Southern South America, Europe as a whole, Western/Central Asia, North and South Africa and Southern Australia (**Fig. 4**).

Habitat suitability was highest in regions under moderate-high water availability, temperate/subtropical climates, and high human influence.

DISCUSSION



The predicted environmental responses were consistent with the known ecology of *C. carpio*. **Moderate-warm temperatures and stable water availability likely favor** growth, feeding activity, recruitment, and reproductive success, **whereas extreme climatic conditions may constrain establishment.**

Human activities appear to play a critical role in shaping the global spread of *C. carpio*. Aquaculture, recreational fisheries, and intentional or accidental translocations can facilitate dispersal beyond natural pathways and promote colonization of new freshwater systems.

Mismatches between occurrence records and predicted suitability indicate that current distributions may also reflect introduction history, artificial habitats, and sampling effort, rather than environmental suitability alone.

The identification of suitable regions with limited current records suggests that **future expansion remains likely**, underlining the need for preventive monitoring and management strategies focused on high-risk areas.

CONCLUSIONS

1. While macroclimatic factors structure *C. carpio* ecological niche, human activities strongly allow it to overcome natural dispersal barriers and establish populations far beyond its climatic limits.
2. Effective management of *C. carpio* requires a shift beyond climate-only approaches towards integrated strategies that explicitly include human water manipulation and connectivity to disrupt spawning and reduce establishment success.
3. Continued improvements in data quality and spatial coverage are essential in under-sampled regions, to increase the robustness of future global invasion assessments.

ARTICLE / THESIS

BIBLIOGRAPHY (p. 19-30)