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1 Article

# 2 Assessing Prospects for Integrating Asian Carp Polyculture in 3 Europe: A Nature-Based Solution Under Climate Change

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19 **Abstract:** Aquaculture's role in addressing food security has grown, with a spotlight on Asian carp  
20 species. Polyculture, cultivating multiple fish species in a single system, is increasingly adopted for  
21 its resource efficiency and economic benefits. This practice, including Asian fish for food and  
22 ornamental purposes, is gaining traction in Europe despite their invasive potential. Rising  
23 temperatures due to climate change offer an opportunity for thermophilic Asian carps  
24 (*Hypophthalmichthys molitrix* and *Aristichthys nobilis*). Thus, using GIS modeling (Maxent), we  
25 identified the possible successful settlement of Asian carp in Northern Europe amidst climate  
26 change. We analyze carp global distribution centers, assess potential carp spread in Europe, and  
27 evaluate their potential suitability for polyculture systems. By 2050, *H. molitrix* may extend its  
28 range to 58–62°N latitude, with a potential 1.7-fold habitat increase, while *A. nobilis*, more  
29 heat-tolerant, may move north to 52–58°N latitude, with a 1.3-fold potential increase. Despite slight  
30 ecological differences from their native habitats, niche modeling indicates these carp can occupy  
31 similar niches in Europe (proven statistically). The eventuality of using Asian species for  
32 polyculture in Europe presents both opportunities and challenges in the face of a changing climate  
33 as long invasion risks are prevented. Envisaging such polyculture yet very carefully for protecting  
34 ecosystems can help food security.

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35 **Keywords:** aquaculture; invasion; climate change; thresholds; species distribution modelling;  
36 Europe.

37 **Key Contribution:** This manuscript presents novel insights into the feasibility of integrating Asian  
38 carps polyculture in Europe as a nature-based solution to climate change. Through comprehensive  
39 GIS modeling and analysis, the study elucidates the potential expansion of Asian carp populations  
40 in European waters, highlighting both opportunities and challenges for sustainable aquaculture  
41 practices in a changing climate as long invasion risks are prevented.

## 1. Introduction

The utilization of aquaculture to address food security concerns has gained significant attraction, with a particular focus on Asian carp species, renowned for their long-standing history in Chinese aquaculture dating back to 475 BC [1]. Polyculture, a practice involving the cultivation of multiple fish species in a single system, has emerged

47 as an intriguing and widely adopted approach [2,3]. By fostering complementary  
48 interactions between species at various levels (trophic, ecological, genetic, etc.),  
49 polyculture promotes the efficient utilization of natural resources and enhances  
50 economic returns [4]. As a result, polyculture of Asian fish, both for food and ornamental  
51 purposes, has recently gained popularity in Europe despite the associated risks of  
52 biological invasion [5,6]. Cyprinids constitute approximately 80% of the total aquaculture  
53 production in freshwater across Central and Eastern Europe [7]. The projected rise in  
54 temperatures due to climate change [7–12] presents an opportunity to envisage these  
55 thermophilic Asian fish species into European fish farms, as long invasion risks are  
56 prevented.

57 Two particularly intriguing candidates are the silver carp *Hypophthalmichthys*  
58 *molitrix* (Valenciennes, 1844) and the bighead carp *Aristichthys* (= *Hypophthalmichthys*)  
59 *nobilis* (Richardson, 1846), both belonging to the Cyprinidae family and capable of  
60 hybridizing in polyculture conditions [13]. The silver carp (*H. molitrix*) is native to most  
61 major Pacific drainages of East Asia, ranging from the Amur River in China to the Xi  
62 Jiang River in Vietnam. It has a wide distribution, extending up to 55°N and even  
63 reported from 58°N in warm waters near an electricity power plant [14]. Silver carps (*H.*  
64 *molitrix*) prefer brackish freshwater environments and inhabit benthopelagic and  
65 potamodromous habitats up to 20 meters deep. Their optimal temperature range is  
66 between 6 and 30°C, with spawning occurring at temperatures above 15°C (typically  
67 18–26°C) in conditions with high current (0.5–1.7 m/s), turbidity, and oxygen  
68 concentration. The silver carp is often mistaken for its more heat-tolerant relative, the  
69 bighead carp (*A. nobilis*), which prefers temperatures ranging from 1°C to 38°C. The  
70 bighead carp's optimal conditions are typically found at 48°N, but it can also thrive in  
71 higher latitudes through aquaculture, utilizing warm water from the cooling systems of  
72 power stations, nuclear power plants, and thermal power plants. The bighead carp is  
73 found in both European and Asian rivers, including the Syrdarya, Amudarya, Karakum  
74 Canal, Terek, Kuban, Dniester, and Prut. It favors deep, turbid waters with temperatures  
75 above 18°C (usually 22–30°C), strong currents, and high oxygen concentrations.  
76 Spawning in bighead carp ceases when water levels drop too low and resumes when  
77 water levels rise. Both species have the potential to expand their range northward to  
78 55°N and beyond in Canada [15].

79 Asian carps were introduced to Europe in the mid-20th century [16–18] and  
80 subsequently spread to North America, where they have established themselves in the  
81 Mississippi and Illinois River basins, the Great Lakes, and other waterways [19]. Asian  
82 carps have been introduced into European waters for phytoplankton control in eutrophic  
83 environments, as these large and voracious filter feeders consume up to 40% of their  
84 body weight per day of phytoplankton. In Ukraine, the introduction of Asian carps has  
85 been associated with positive effects, including the active control of summer  
86 phytoplankton blooms, recycling of detritus, and cleansing of vegetation from  
87 reclamation channels [18]. Despite Asian carps have significant invasive potential, they  
88 also constitute a potential source of food. The intentional introduction of Asian carps in  
89 many European countries has led to cases of self-reproduction in the wild, such as in the  
90 Danube and Tisza River basin, an irrigation canal network in Northern Italy [17–22].

91 However, the voracious appetite of Asian carps has led to concerns about their  
92 ecological impacts, as they can potentially displace native fish species. For instance,  
93 Asian carps have been found to account for 97% of the total fish biomass in a Missouri  
94 National Wildlife Refuge (MICRA 2002) [23]. Opinions on the ecological impacts of Asian  
95 carps vary. Some argue that their voracious consumption of phytoplankton can  
96 positively control water blooms, while others express concerns about their potential to  
97 reduce aquatic vegetation, negatively affecting native aquatic herpetofauna, such as the  
98 European pond turtle (*Emys orbicularis* (Linnaeus, 1758)) and amphibians (e.g., newts)  
99 [24]. Thus, a comprehensive assessment of their ecological impacts is still lacking  
100 [12,23,25].

The literature emphasizes the need of GIS modeling and ecological niche models for studying and managing the processes of fish species invasions. However, the literature only mentions either local models for other regions (such as North America, Africa, etc.) or the use of other fish species for modeling, which highlights the uniqueness of our work, especially in assessing the ecological niches of these fish species – *H. molitrix* and the bighead carp *A. nobilis* [26-30]. The application of GIS modeling not only allows for accurate prediction of the potential spread of invasive species in new ecosystems but also effectively plans measures for their control and prevention of negative impacts on local biodiversity and economy.

The feasibility of raising Asian carp species in more northerly European regions remains a topic of debate, particularly in light of the potential freshwater shortages and general warming expected to accompany climate change (IPCC, 2021) [31,32]. Our study aims to address this question by investigating three key areas:

1. Identifying global carp distribution centers: Utilizing species distribution modeling techniques, we seek to pinpoint and compare the primary centers of carp distribution worldwide.

2. Analyzing carp spread in Europe: We delve into the likelihood and prospects for the expansion of Asian carp populations in Europe, particularly in northeastern regions, and explore the factors influencing this spread.

3. Assessing polyculture potential: We examine the viability of incorporating Asian carp species into polyculture systems by comparing their natural biotopes (ecological niches, niche clustering) to those found in their new distribution centers in Europe and America.

The results of our study will contribute to a more comprehensive understanding of the potential for Asian carp aquaculture in Northern Europe, shedding light on the opportunities and challenges associated with this practice in the context of climate change and biological invasions.

Conducted against the backdrop of climate change, this research underscores the pressing need for sustainable and adaptive measures in conservation biology. With a specific focus on Asian carps, regarded as a pivotal species for polyculture in Europe, the study seeks to address challenges posed by invasive species through environmentally friendly strategies.

## 2. Materials and Methods

The methodology employed leverages GIS models, offering a spatial approach to comprehensively evaluate the feasibility and impact of Asian carp polyculture in Europe. This assessment incorporates crucial considerations of environmental, geographical, and climatic factors, providing a holistic perspective for sustainable conservation solutions.

### 2.1. Occurrence data collection

An extensive literature review was conducted, and databases were compiled to include point records for both *H. molitrix* and *A. nobilis*. These records encompassed original and literary sources, UKRBIN data, and GBIF.org data (2022) [33,34]. All records were verified to eliminate duplicates. To address sampling bias, the nearest neighbor distance method (implemented using the 'ntbox' package in R) [35] was employed to thin the data. Occurrence points located within 0.1 units (km) of each other were removed to mitigate errors arising from spatial autocorrelation. Consequently, the number of points was substantially reduced to 6552: 982 for *H. molitrix* (5896 records from GBIF) and 692 for *A. nobilis* (2290 records from GBIF).

### 2.2. Environmental data

For building the species distribution models (SDMs) we used bioclimatic variables from the CliMond dataset (<https://www.climond.org/>, (accessed 27 December 2020),

152 A1B) [9,10,36]. We used 35 bioclimatic variables for the time period around 1975  
153 (1970-2000), 2050 (2041-2060) for GIS modeling. The following bioclimatic variables  
154 (Climond) were employed (resolution 2.5 arc-minutes, i.e. ~5 km). Of 35 bioclimatic  
155 variables, highly correlated (>0.7) predictors were removed using the 'virtualspecies'  
156 package in R, resulting in a selection of 16 bioclimatic variables for both 1975 (1970-2000),  
157 and 2050 (2041-2060). The selected bioclimatic variables (Climond) were (Table S1):  
158 bio01, Annual mean temperature (°C), bio02, Mean diurnal temperature range (mean  
159 (period max-min)) (°C), bio03, Isothermality (Bio02÷Bio07), bio04, Temperature  
160 seasonality (C of V), bio06, Min temperature of coldest week (°C), bio07, Temperature  
161 annual range (Bio05-Bio06) (°C), bio08, Mean temperature of wettest quarter (°C), bio10,  
162 Mean temperature of warmest quarter (°C), bio11, Mean temperature of coldest quarter  
163 (°C), bio12, Annual precipitation (mm), bio14, Precipitation of driest week (mm), bio15,  
164 Precipitation seasonality (C of V), bio17, Precipitation of driest quarter (mm), bio25,  
165 Radiation of driest quarter (W m<sup>-2</sup>), bio30, Lowest weekly moisture index, bio34, Mean  
166 moisture index of warmest quarter.

167 We also used 13 environmental variables - 12 variables from the Near-global  
168 environmental information for freshwater ecosystems in 1 km resolution (EarthEnv  
169 NGEI, characterizing land cover, <http://www.earthenv.org/>) [37] and the Global Aridity  
170 Index\_ET0 (Global-AI\_ET0). Aridity is usually expressed as a generalized function of  
171 precipitation, temperature and reference evapo-transpiration (ET0): the Aridity Index  
172 (<https://csidotinfo.wordpress.com/>) [38] can be used to quantify precipitation availability  
173 over atmospheric water demand (Table S2): 1.Evergreen/deciduous needleleaf trees;  
174 2.Evergreen broadleaf trees; 3.Deciduous broadleaf trees; 4.Mixed/other trees; 5.Shrubs;  
175 6.Herbaceous vegetation; 7.Cultivated and managed vegetation; 8.Regularly flooded  
176 shrub/herbaceous vegetation; 9.Urban/built-up; 10.Snow/ice; 11.Barren lands/sparse  
177 vegetation; 12.Open water; 13.Global Aridity Index.

178 Ecological niche and species distribution modeling (SDM) techniques have been  
179 applied to investigate the potential home range of invasive species in new environments.  
180 The Maxent algorithm (version 3.4.4) [39,40], which was run with 25 replicates, was  
181 employed using the default settings. Unlike other distributional modeling approaches,  
182 Maxent only requires presence and background data.

### 183 2.3. Model building

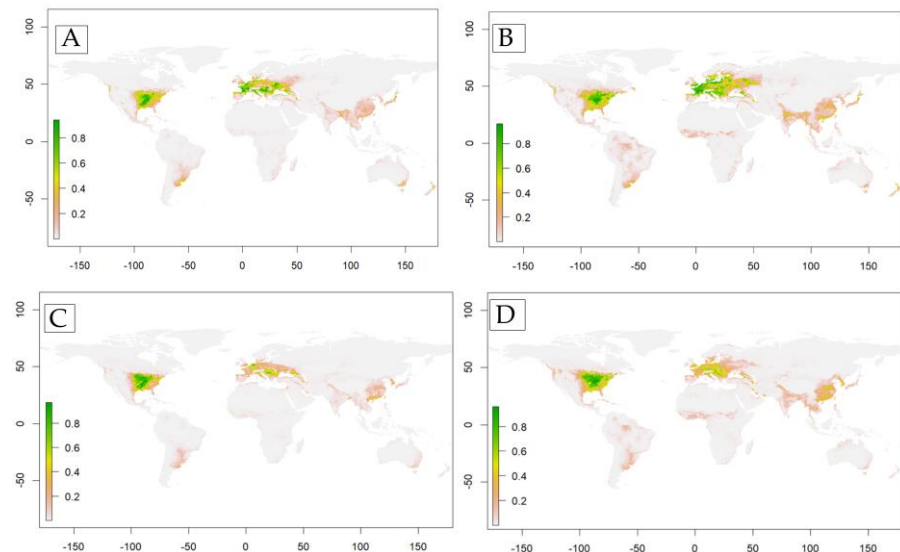
184 Ecological niche and species distribution modeling (SDM) techniques have been  
185 extensively applied to explore the potential home range of invasive species in new  
186 environments. In this study, we employed the Maxent algorithm (version 3.4.4),  
187 developed by Phillips et al. (2005) and Peterson et al. (2008) [39,40], to model the potential  
188 distribution of Asian carps in Europe. Maxent is a robust and widely used SDM  
189 algorithm that can effectively model species distributions using presence-only data,  
190 unlike other distributional modeling techniques that require both presence and absence  
191 data. We conducted modeling at the scale of the entire distribution area, utilizing  
192 distribution points from both the natural range and recorded introductions on other  
193 continents. This approach allowed us to incorporate the full extent of the species'  
194 potential ecological niche and identify areas that may be suitable for their establishment  
195 and spread. This revision clarifies the purpose of using the Maxent algorithm and  
196 emphasizes its ability to utilize presence-only data, which is particularly relevant for  
197 invasive species management. It also highlights the importance of considering  
198 distribution points from both the natural range and recorded introductions to capture the  
199 full extent of the species' potential distribution.

200 Evaluation metrics were used to measure the performance of the SDMs and  
201 included the Partial ROC [9,40] and the confusion matrix. The performance of the Maxent

model is usually evaluated by the threshold-independent receiver operating characteristic (ROC) approach, where the calculated area under the ROC curve (AUC) is considered as a measure of prediction success [41]. The ROC curve is a graphical method that represents the relationship between the false-positive fraction (one minus the specificity) and the sensitivity for a range of thresholds. It has a range of 0–1, with a value greater than 0.5 indicating a better-than-random performance event [42]. A rough classification guide is the traditional academic point system: very good (0.8–0.9) and excellent (0.9–1.0). Models were evaluated using the true skill statistic (TSS) [43]. TSS values range from -1 to +1, with -1 corresponding to systematically wrong predictions and +1 to systematically correct predictions; TSS values <0.4 are considered poor, >0.4 useful and good. GIS-modelling was accomplished using SagaGis, QGIS. Statistical processing of the obtained data was carried out in PAST (Principal components analysis (PCA)) [44].

### 3. Results

As a result of the modeling, the potentially most suitable territories for the distribution of both species of Asian carps were identified, including the native range - Asia. According to the available data and GIS modeling, three main centers could be distinguished where the most favorable current conditions were identified for carps (Figure 1, Binomial tests [35]): (1) southeast of North America, (2) Europe (quite a wide range), and (3) Southeast Asia and the Far East. In the perspective times by 2050, three additional areas were identified: (4) north and East of South America, (5) Northern tropical Africa, and Indian area, and (6) Southeast Australia.



**Figure 1.** Result of the analysis of Binomial tests SDMs (green color > 0.5, CliMond dataset, [35]): *H. molitrix* - (A) current; (B) 2050 (2041–2060) and *A. nobilis* - (C) current; (D) 2050 (2041–2060).

In terms of discrimination accuracy, the Maxent model (SDMs, CliMond) showed excellent performance: AUC > 0.9. For both *H. molitrix* and *A. nobilis*, useful TSS values were obtained, respectively TSS=0.636, and TSS=0.572.

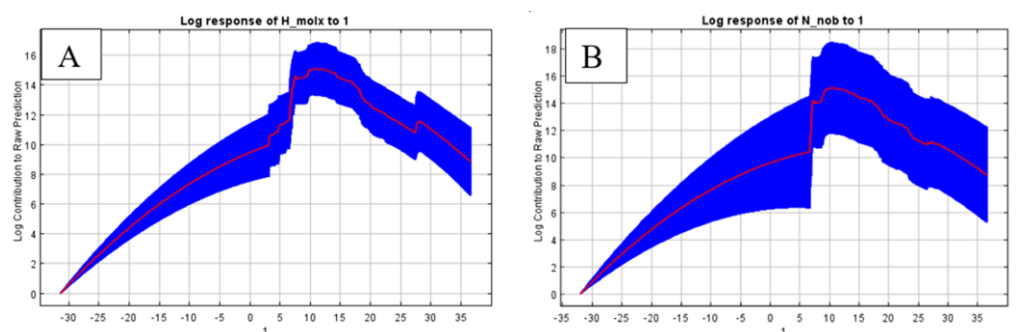
The distribution of two carp species was influenced by temperature factors, particularly "Annual mean temperature" (bio1) that contributed to 22–24% to the model, most likely due to the dependence of juvenile reproduction and growth on sufficiently warm waters (Table 1).

For the more thermophilic *A. nobilis*, the favorable range of "Annual mean temperature" (bio1) was 7°C to 27°C, and the optimal range was 9°C to 17°C, with the response curve peaking around 10°C (Figure 2). However, these species have specific requirements under certain conditions, particularly during breeding. This is evident from the influence on the distribution of these fish species of other important factors besides temperature, such as "Precipitation of driest quarter" (bio17), "Isothermality" (bio3), and "Lowest weekly moisture index" (bio30) (Table 1).

For *H. molitrix*, the favorable range of "Annual mean temperature" (bio1) was between 3°C and 27°C, with an optimal range between 8°C and 17°C (Figure 2-3).

**Table 1.** Results of modeling the spread of Asian carps (CliMond and EarthEnv NGEI, Maxent).

Variable	Percent contribution	Permutation importance
<i>H. molitrix</i>		
CliMond (Table S1)		
bio1. Annual mean temperature (°C)	22.0	26.6
bio17. Precipitation of driest quarter (mm)	19.2	1.2
bio3. Isothermality	14.1	6.3
EarthEnv NGEI (Table S2)		
lc_avg_09. Urban/built-up	34.4	10.0
lc_avg_04. Mixed/other trees	12.1	18.1
<i>A. nobilis</i>		
CliMond (Table S1)		
bio1. Annual mean temperature (°C)	24.0	44.0
bio3. Isothermality	18.3	8.8
bio30. Lowest weekly moisture index	9.5	0.4
EarthEnv NGEI (Table S2)		
lc_avg_09. Urban/built-up	29.1	11.8
lc_avg_07. Cultivated and managed vegetation	16.4	14.2

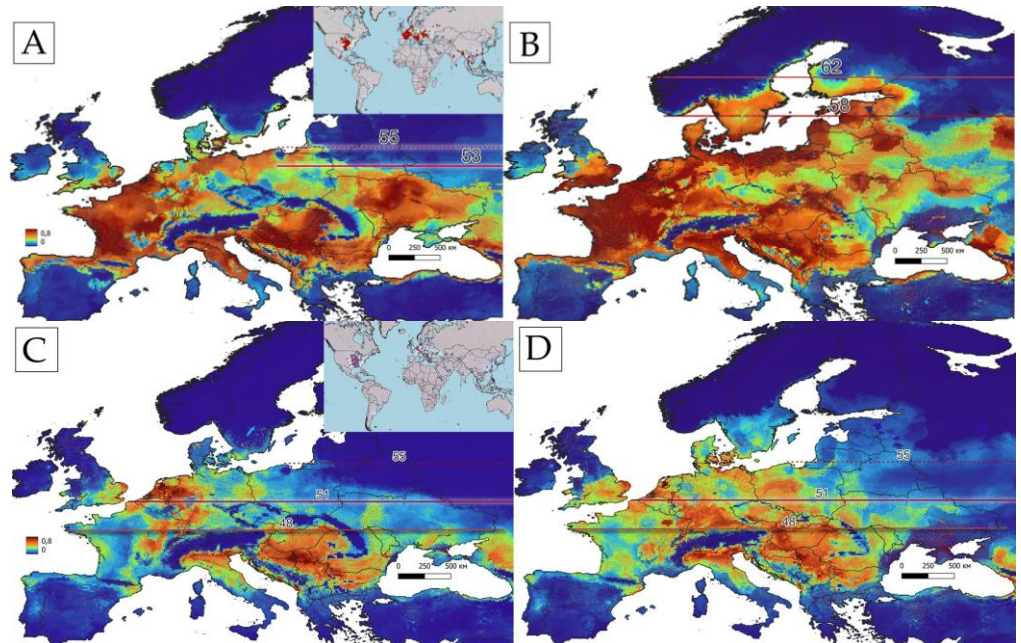


**Figure 2.** Response curves generated by Maxent of Asian carps for the variable «Annual mean temperature» (°C, bio1): *H. molitrix* - (A); *A. nobilis* - (B) (Table 1).

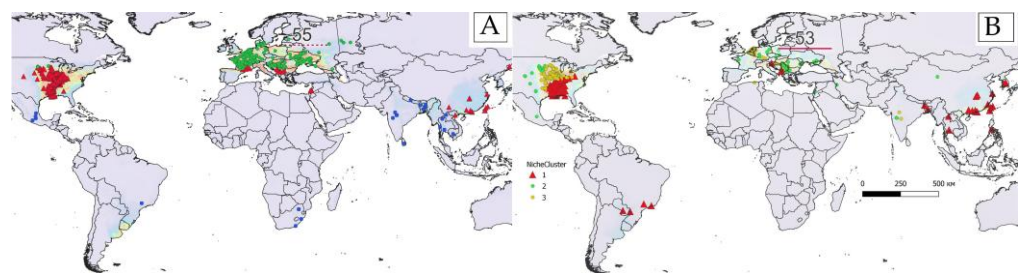
GIS modeling revealed that Asian carp are anticipated to shift their range northward in Europe in response to climate change [12,24]. By 2050, projections suggest that *H. molitrix* may extend its range, with a potential 1.7-fold increase in habitat, while *A. nobilis*, being more heat-tolerant, may migrate northward, with a potential 1.3-fold increase (Figure 3).



The results of niche clustering, employing techniques such as k-means clustering, were visualized to illustrate variations in global climatic conditions across continents for two species of carps. This approach categorizes ecological niches by integrating geographic and environmental variables, offering insights into habitat distribution patterns and ecological diversity (Figure 4).



**Figure 3.** Potential (probabilistic) model of Asian carp expansion built in the Maxent program in Europe of based on dataset CliMond (red color > 0.5): *H. molitrix* - (A) current; (B) CliMond dataset 2050 (2041-2060) and *A. nobilis* - (C) current; (D) CliMond dataset 2050 (Table S1).



**Figure 4.** Niche clustering (Geographic space, CliMond current) for (A) - *H. molitrix*, 55°N; (B) - *A. nobilis*, 53°N. Differently coloured marks represents different biotopes where the fish species was registered according to data collected and which has combination of different climatic factors (marked: 1 red triangle - close to home region, 2 green circle - westernmost finds and 3 orange circles - intermediate conditions).

#### 4. Discussion

The silver carp *H. molitrix* and bighead carp *A. nobilis* are two species of Asian carps that have become invasive in many parts of the world, including Europe. These fish can have significant negative impacts on native ecosystems. Understanding the factors that affect their distribution is important for managing their spread. Because these species are actively used in aquaculture, particularly in fisheries, it is crucial to investigate the influence of other climatic factors on their distribution in the northern portion of their range.

Our results show that temperature, namely annual mean temperature, is the main factor affecting the distribution of Asian carps in Europe. Given the critical role of



283 temperature factors in shaping the distribution of these Asian fish species, our analysis  
284 suggests that the potential suitable habitat for *H. molitrix* in Europe currently lies within  
285 latitudes between 53–55° N. However, by 2050, projections indicate a northward shift in  
286 its range, extending up to 58–62° N (Figure 3). This expansion will encompass Latvia and  
287 areas further north to Norway, Sweden, and Finland. Potentially suitable habitats for the  
288 more thermophilic species *A. nobilis* are primarily located in the Danube, Dniester, and  
289 Seversky Donets basins, spanning up to 48–51° N. Forecast projections suggest that by  
290 2050, this species could potentially expand its range northward to 52–55° N, reaching up  
291 to 58° N around the Baltic Sea (Figure 3). These findings corroborate former studies  
292 reporting that most thermophilic freshwater animals are likely to experience range shifts  
293 in the future [12,24,45]. According to former forecasts, self-reproduction of silver carps  
294 will likely occur in the Netherlands by 2050 [30]. While temperature factors play a  
295 significant role in determining the distribution of Asian carps, these fish species have  
296 demonstrated a remarkable ability to adapt to colder climates. In northern regions, they  
297 are more likely to survive in artificially created water systems, such as ponds, reservoirs,  
298 and canals. These environments provide a more stable temperature regime compared to  
299 natural water bodies, enabling the fish to persist even in colder conditions. Adapting to  
300 colder temperatures also requires the ability to migrate to wintering grounds where there  
301 is sufficient oxygen. As water temperatures drop below 10°C, the behavior of fish  
302 changes. They form schools and prepare for wintering by moving to deeper parts of  
303 water bodies, where oxygen levels are typically higher. In the context of aquaculture,  
304 maintaining adequate oxygen levels in stagnant water bodies during the winter months  
305 is crucial for the successful wintering of the fish population. This may necessitate  
306 additional aeration measures, such as the use of air pumps or bubblers. Overall, the  
307 adaptability of Asian carps to colder environments poses a significant challenge for  
308 managing their spread. Understanding their survival strategies and implementing  
309 effective control measures are essential for mitigating the negative impacts of these  
310 invasive species.

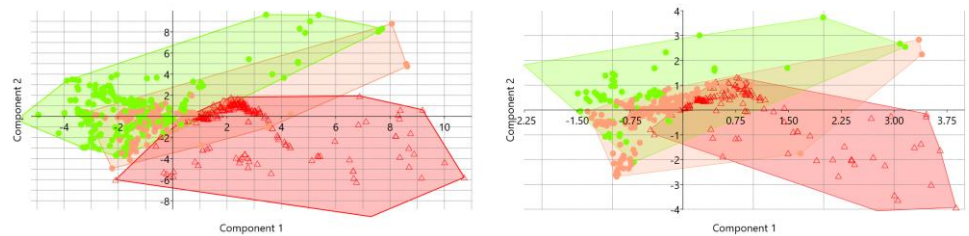
311 As species cultured in warm waters discharged from power plants, Asian carps have  
312 demonstrated an ability to thrive in more northern regions, as documented on open  
313 databases (Fishbase.org, FAO.org). This adaptation is partly attributed to their ability to  
314 utilize warm water discharges from power plants. Additionally, the widespread  
315 distribution of these thermophilic herbivorous Asian fish is facilitated by the stocking of  
316 captive-bred fry. For these species to successfully reproduce in the wild, specific  
317 conditions are required. Water temperatures between 22°C–28°C, along with suitable  
318 water flow and changes in water levels, can stimulate natural fish reproduction and  
319 favorably impact the development of benthopelagic fish eggs. While fry growth can  
320 occur in stagnant water bodies, these conditions are unsuitable for reaching maturity and  
321 triggering reproduction.

322 Utilizing niche clustering analysis such as clustering algorithms like K-means  
323 clustering [46], our study has yielded detailed insights into the ecological preferences of  
324 both Asian carp species (Figure 4). This approach, known as Hutchinson's duality, enables  
325 researchers to identify distinct clusters or groups of similar ecological conditions within a  
326 geographic area. Notably, *H. molitrix* exhibits a broader distribution across various  
327 ecological niches compared to second species. Moreover, this analysis has illuminated  
328 distinctions in bioclimatic parameters within the native habitats of these Asian alien fish  
329 species, as illustrated in Figure 4. Remarkably, regions with analogous conditions have  
330 been identified in the southern sectors of North America and in limited areas of South  
331 America and Europe, as indicated by red triangles in Figure 4. These findings underscore  
332 the remarkable adaptability of Asian carps and their potential to thrive across a broader  
333 range of climatic conditions, including those conventionally considered inhospitable to  
334 their survival.

335 Despite subtle ecological disparities from their native environments, niche modeling  
336 provides compelling evidence suggesting that these carp species can effectively occupy

similar ecological niches within Europe. This conclusion is bolstered by rigorous statistical analysis, underscoring the adaptability of Asian carps to diverse environmental conditions and their potential to establish sustainable populations in European waters.

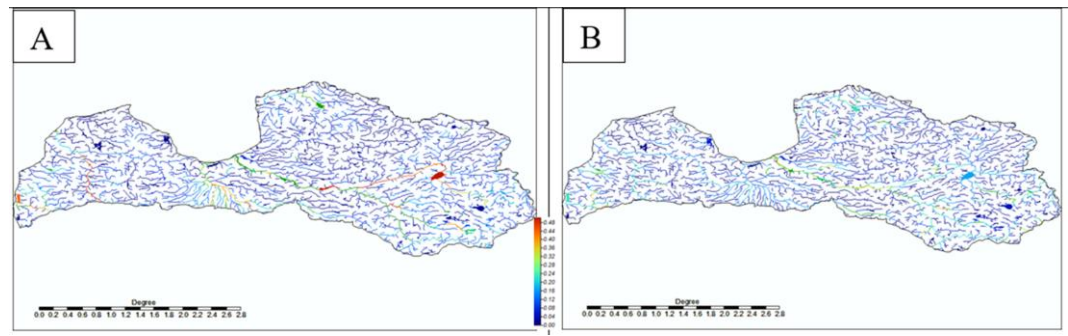
To strengthen the justification for calibrating Asian carp models for our purpose using occurrences from both the native and the invaded range, and to detect niche shift, we employed principal component analysis (PCA) [47]. This technique allowed us to compare the position of occurrences from these ranges in the bioclimatic space of the variables (i.e., predictors) with the greatest permutation importance (listed in Table 1). PCA of the predictors revealed two significant axes (PC1 and PC2) of climatic variation, which explained around 60% of the total variance. Plotting the occurrences in the dimensions of the first two PCs revealed the environmental space occupied by the introduced population of Asian carps in Europe and America (round labels). This occupied space appears to be partially overlapped with that of the Asian and similar (including native) occurrences (red triangle), indicating a niche shift (Figure 5).



**Figure 5.** Triplot showing the bioclimatic spaces for the three groups of occurrence records (Niche clustering, Fig.4) of Asian carps (*H. molitrix* - (A); *A. nobilis* - (B)), representing the suitability for breeding including native (red triangle) and invaded (green and orange circles) ranges (marked in Figure 4).

Despite their shared thermophilic nature, the two Asian carp species exhibit subtle ecological distinctions, indicating a degree of specialization under natural conditions. Comparing with the modeling results presented in the literature, where conditions in the native range of carps are compared with those in North America, they also emphasize the unique conditions and advantages specifically in the native range [26-28]. However, when introduced to new environments, these fish demonstrate remarkable adaptability, a characteristic common among many invasive fish species. This revision emphasizes the ecological differences between the two carp species and their ability to adapt to new environments, highlighting the potential for further range expansion and colonization. The presence of specific abiotic conditions, such as non-freezing waters with sufficient depth and adequately mobile water with a high oxygen content, plays a critical role in the distribution of Asian carps.

To delineate the key determinants of potential suitability habitat for fish in Northern Europe [32], we employed GIS modeling and 13 environmental variables [37,38] - comprehensive ecological data for freshwater ecosystems, focusing on Latvia as a case study. These data encompass spatially continuous, and freshwater-specific environmental variables, including river system characteristics, land cover features, and anthropogenic impacts. Our study reveals that the acclimatization and distribution of *H. molitrix* and *A. nobilis* in Europe are strongly linked to factors such as: "urban/built-up areas (9)" - may be due to the use of thermophilic waters, also, "mixed/other trees (4)" and "cultivated and managed vegetation (7)" - may be due to the use of artificial fish ponds (Figure 6, Table 1). Under current conditions, *H. molitrix* appears to be the more likely successful species among the two Asian carps examined, given its enhanced tolerance to extreme temperatures and anthropogenic factors, especially in Northern Europe (Figure 6).



**Figure 6.** Potential (probabilistic) model of Asian carps (*H. molitrix* - (A); *A. nobilis* - (B)) in Northern Europe using the example of Latvia, expansion built in the Maxent program based on dataset 13 environmental variables (red color > 0.5; EarthEnv NGEL, Table S2).

Thus, our findings demonstrate that under current climatic conditions in Northern Europe, Asian carps rely on anthropogenic factors and support, but in the future, more favorable conditions may emerge for these thermophilic fish. Additionally, given the hybridization of these species, such adaptation of invasive fish holds evolutionary significance in new condition. However, questions remain regarding the ecological safety of native amphibian and fish species and ecosystems as a whole, necessitating ongoing monitoring and control.

## 5. Conclusions

Our research shows that the distribution of Asian carps in Europe is likely to shift northward in response to climate change. This necessitates the development of proactive pan-European management plans to curb the future expansion of these exotic invasive species. We all but call for the introduction of invasive species in intact European ecosystems for aquaculture or other reasons. This is why understanding which geographical areas are potentially suitable for these fish species and their potential spread is crucial. Our models indicate that by 2050, waters, including those of Northern Europe, will provide suitable conditions for Asian carps. Interestingly, despite exhibiting slight ecological niche differences in their native range, these two species can occupy the same biotopes and thrive in polyculture, as demonstrated by our models. Thus, proving the advantage of polycultures not only in economic and food value, but also showing the evolutionary potential of such aquacultures, because these species, by hybridizing, provide new opportunities for offspring to survive in new extreme conditions where native species may not. However, the northward range shift of Asian carps poses a significant challenge for European ecosystems, and effective management strategies are essential to prevent the negative impacts of these invasive species. It is the understanding of the main key points that can help develop sustainable management plans at the international level [47]. To harness the potential benefits of polyculture while minimizing ecological disruptions, several key measures are recommended:

**Thorough impact assessments:** Comprehensive evaluation of the potential ecological consequences of Asian carp species occurrence into Northern European ecosystems are essential (including the introduction of health-threatening infections and parasites).

**Monitoring and management strategies:** Effective monitoring and management strategies are critical to mitigate any negative impacts on native fauna and ensure the sustainable development of aquaculture practices.

**Collaborative approach:** Collaboration among scientists, policymakers, and stakeholders is paramount to developing sustainable aquaculture practices that balance food production with the preservation of native biodiversity.

By understanding their distribution patterns and ecological requirements of the Asian carps, we can develop targeted interventions to control their spread while protecting native biodiversity.

**Supplementary Materials:** The following supporting information can be downloaded at: [www.mdpi.com/xxx/s1](http://www.mdpi.com/xxx/s1), Table S1: Bioclimatic variables (35) from the CliMond dataset (Kriticos et al., 2014, (<https://www.climond.org/>)), Table S2: Environmental variables (13) from the Near-global environmental information for freshwater ecosystems (EarthEnv NGEI, 12 variables characterizing land cover, Domisch et al., 2015, <http://www.earthenv.org/>) and the Global Aridity Index\_ET0 (Global-AI\_ET0).

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**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Data derived from public domain resources: Environmental data - <https://www.climond.org/>, <http://www.earthenv.org/>, <https://csidotinfo.wordpress.com/>. Occurrence data collection - *Aristichthys nobilis* (Richardson, 1846) (= *Hypophthalmichthys nobilis*) GBIF.org (07 January 2022) GBIF Occurrence Download <https://doi.org/10.15468/dl.rbcrky>, *Hypophthalmichthys molitrix* (Valenciennes, 1844) GBIF.org (07 January 2022) GBIF Occurrence Download <https://doi.org/10.15468/dl.46yqnd>. The data that supports the findings of this study are available in the supplementary material of this article.

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