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Assessing Prospects of Integrating Asian Carp Polyculture in Europe: A Nature-Based Solution under Climate Change?

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

Keywords: aquaculture; invasion; climate change; thresholds; species distribution modeling; Europe

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

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

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

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

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

The literature emphasizes the need for 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 the 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 issue 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, this 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 on 27 December 2020), A1B) [9,10,36]. We used 35 bioclimatic variables for the time periods around 1975 (1970–2000) and 2050 (2041–2060) for GIS modeling. The following bioclimatic variables (CliMond) were employed (resolution of 2.5 arc-minutes, i.e., ~5 km). Of the 35 bioclimatic variables, the highly correlated (>0.7) predictors were removed using the 'virtualspecies' package in R, resulting in a selection of 16 bioclimatic variables for both 1975 (1970–2000) and 2050

(2041–2060). The selected bioclimatic variables (CliMond) were (Table S1): bio01, annual mean temperature (°C); bio02, mean diurnal temperature range (mean (period max–min)) (°C); bio03, isothermality (Bio02÷Bio07); bio04, temperature seasonality (C of V); bio06, min temperature of coldest week (°C); bio07, temperature annual range (Bio05-Bio06) (°C); bio08, mean temperature of wettest quarter (°C); bio10, mean temperature of warmest quarter (°C); bio11, mean temperature of coldest quarter (°C); bio12, annual precipitation (mm); bio14, precipitation of driest week (mm); bio15, precipitation seasonality (C of V); bio17, precipitation of driest quarter (mm); bio25, radiation of driest quarter (W m^{-2}); bio30, lowest weekly moisture index; bio34, mean moisture index of warmest quarter.

We also used 13 environmental variables—12 variables from the near-global environmental information for freshwater ecosystems at a 1 km resolution (EarthEnv NGEI, characterizing land cover, http://www.earthenv.org/, accessed on 20 January 2023) [37] and 1 the Global Aridity Index_ET0 (Global-AI_ET0). Aridity is usually expressed as a generalized function of precipitation, temperature, and reference evapo-transpiration (ET0). The Aridity Index (https://csidotinfo.wordpress.com/, accessed on 20 January 2023) [38] can be used to quantify the precipitation availability over atmospheric water demand (Table S2). The variables were as follows: (1) evergreen/deciduous needleleaf trees; (2) evergreen broadleaf trees; (3) deciduous broadleaf trees; (4) mixed/other trees; (5) shrubs; (6) herbaceous vegetation; (7) cultivated and managed vegetation; (8) regularly flooded shrub/herbaceous vegetation; (9) urban/built-up; (10) snow/ice; (11) barren lands/sparse vegetation; (12) open water; (13) Global Aridity Index.

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

2.3. Model Building

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

Evaluation metrics were used to measure the performance of the SDMs and 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, and >0.4 as useful and good. GIS-modeling 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 their 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. From the perspective of time, 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.

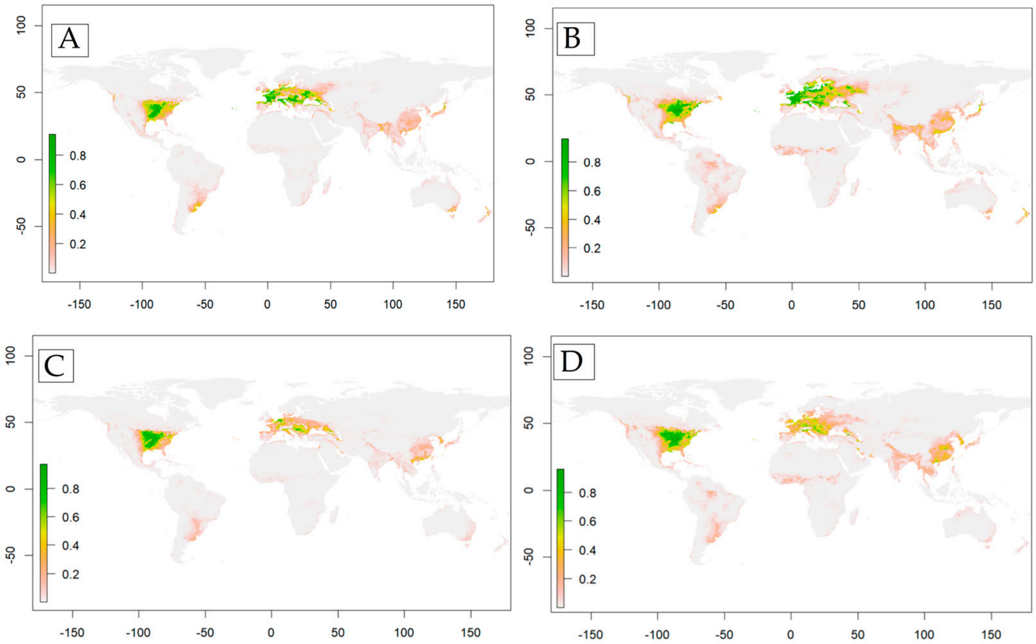


Figure 1. Results of the analysis of SDM binomial tests (green color > 0.5, CliMond dataset [35]). *H. molitrix:* (**A**) current; (**B**) 2050 (2041–2060). *A. nobilis*: (**C**) current; (**D**) 2050 (2041–2060).

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: TSS = 0.636 and TSS = 0.572, respectively.

The distribution of two carp species was influenced by temperature factors, particularly the "annual mean temperature" (bio1), which contributed 22–24% to the model and is 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 the "annual mean temperature" (bio1) was 7 °C to 27 °C, and the optimal range was from 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).

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

Variable	Contribution Percent	Permutation Importance
	H. molitrix	
	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
	A. nobilis	
	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

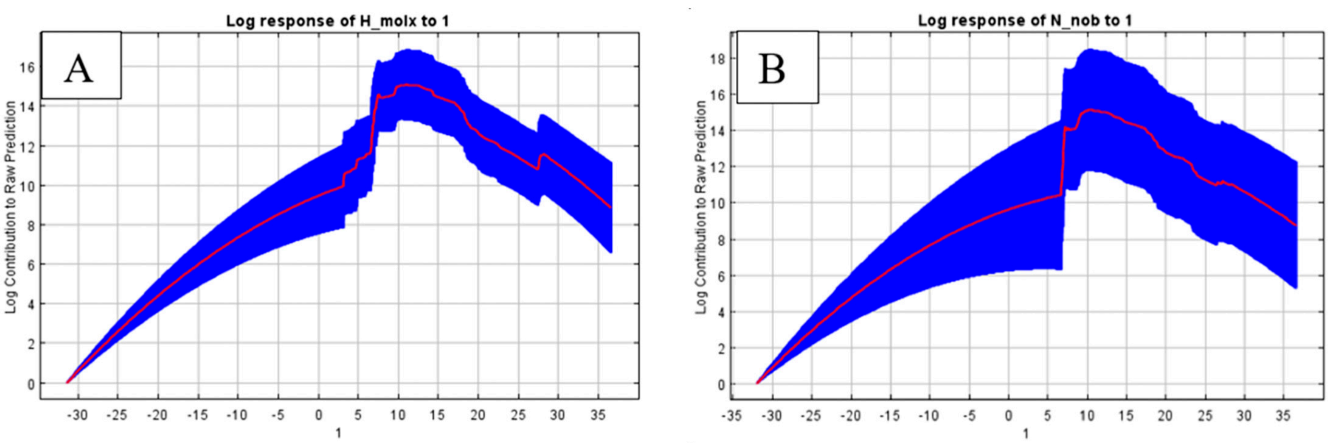


Figure 2. Response curves generated by Maxent of Asian carps for the variable "annual mean temperature" (°C, bio1): *H. molitrix* (**A**); *A. nobilis* (**B**) (Table 1).

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

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 the 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).

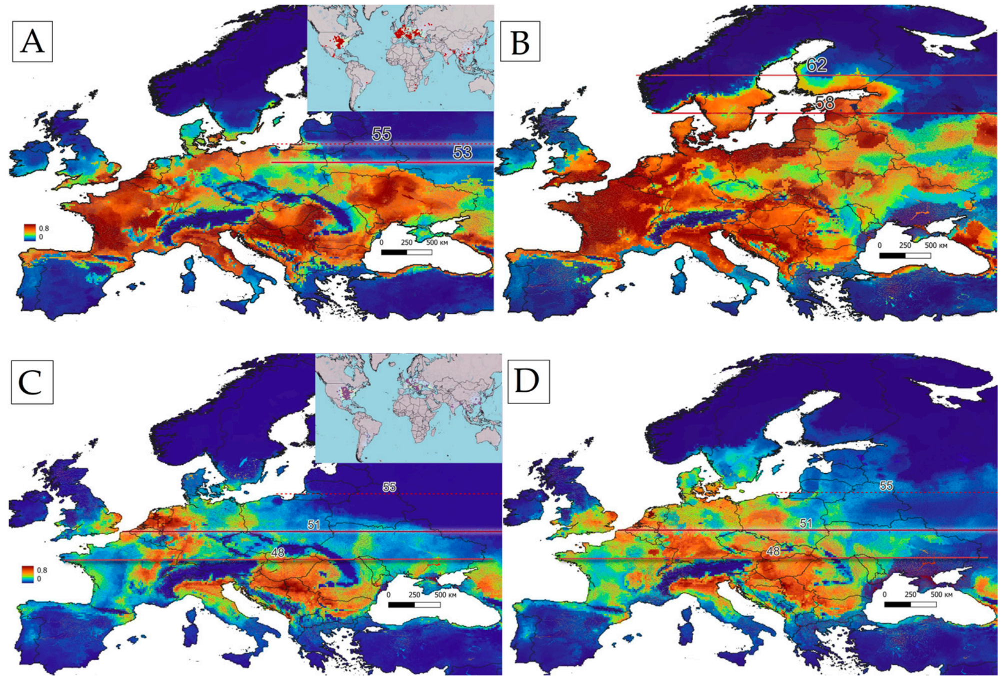


Figure 3. Potential (probabilistic) model of Asian carp expansion built in the Maxent program in Europe based on CliMond dataset (red color > 0.5). *H. molitrix*: (**A**) current (dotted line marks—55° N, red line marks—53° N); (**B**) CliMond dataset 2050 (thin line—62° N, thick red line—58° N). *A. nobilis* (dotted line—55° N; thin line—51° N, thick red line—48° N): (**C**) current; (**D**) CliMond dataset 2050 (Table S1).

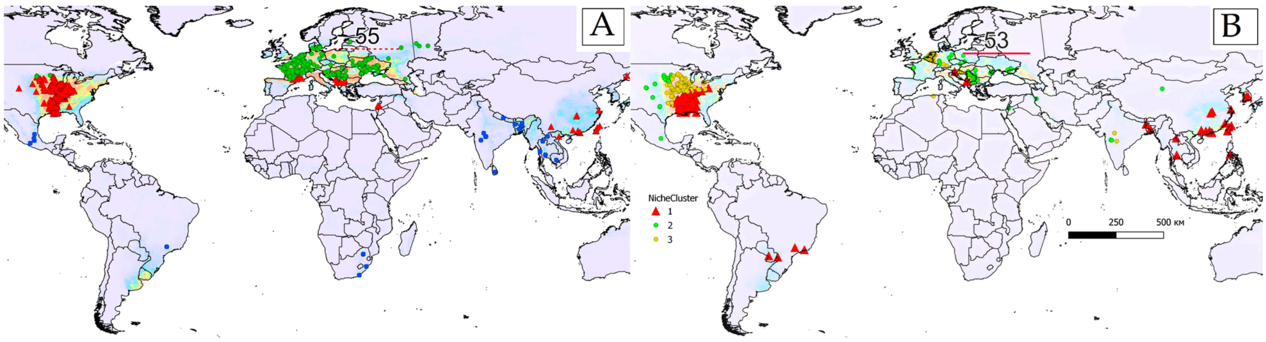


Figure 4. Niche clustering (geographic space, current CliMond) for (**A**) *H. molitrix*, 55°N; (**B**) *A. nobilis*, 53° N. Differently colored marks represent different biotopes where the fish species were registered according to the data collected and which have the combination of different climatic factors. Red triangle (1)—close-to-home region; green circle (2)—westernmost finds; and orange circles (3)—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.

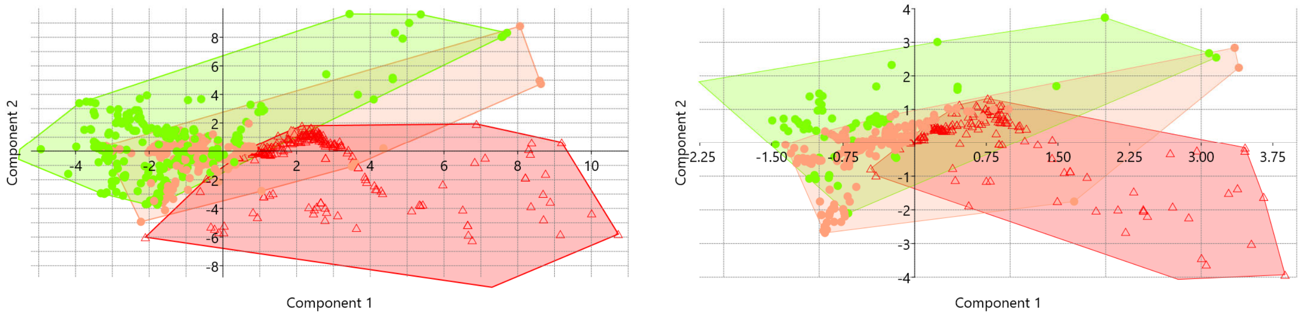
Our results show that the temperature, namely the annual mean temperature, is the main factor affecting the distribution of Asian carps in Europe. Given the critical role of temperature factors in shaping the distribution of these Asian fish species, our analysis suggests that the potential suitable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

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

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

Despite subtle ecological disparities from their native environments, niche modeling 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 in these ranges in the bioclimatic space of the variables (i.e., predictors) with the greatest permutation importance (listed in Table 1). The PCA of the predictors revealed two significant axes (PC1 and PC2) of climatic variation, which explain 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).



(**A**) (**B**)

Figure 5. Triplot showing the bioclimatic spaces of the three groups of occurrence records (niche clustering, Figure 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. Compared to 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 suitable habitats 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)", which may be due to the use of thermophilic waters; "mixed/other trees (4)" and "cultivated and managed vegetation (7)", which may be due to the use of artificial fish ponds (Figure 6, Table 1). Under the current conditions, *H. molitrix* appears to be the more likely successful species between the two Asian carps examined, given its enhanced tolerance to extreme temperatures and anthropogenic factors, especially in Northern Europe (Figure 6).

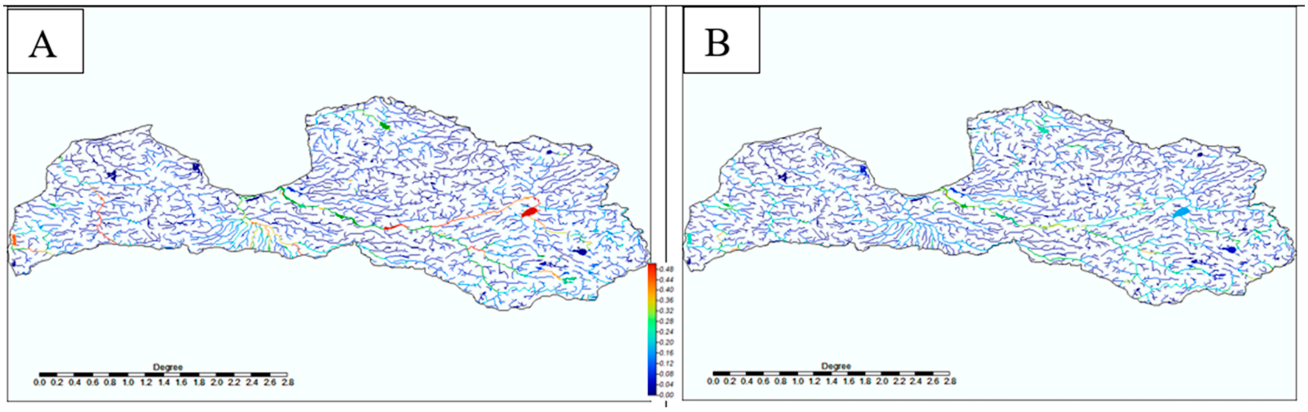


Figure 6. Potential (probabilistic) model of Asian carps (*H. molitrix* (**A**); *A. nobilis* (**B**)) in Northern Europe using the example of Latvia. The expansion was built in the Maxent program based on a dataset of 13 environmental variables (red color > 0.5; EarthEnv NGEI, Table S2).

Thus, our findings demonstrate that under the 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 under new conditions. 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 alien species in intact European ecosystems for aquaculture or any 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. This not only proves the advantage of polycultures for their economic and food value but also shows 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. Understanding the main key points 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 evaluations of the potential ecological consequences of Asian carp species occurrence in 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 for mitigating any negative impacts on native fauna and ensuring 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 the distribution patterns and ecological requirements of 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: https://www.mdpi.com/article/10.3390/fishes9040148/s1, Table S1: Bioclimatic variables (35) from the CliMond dataset, [36], (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, [37], http://www.earthenv.org/) and the Global Aridity Index_ET0 (Global-AI_ET0, [38]).

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Institutional Review Board Statement: Ethics Committee or Institutional Review Board approval are not required for this manuscript. In this work, we used the data of national monitoring programs conducted by the authors for the Nature Conservation Agency of France, Latvia, and Ukraine. We also used open databases (GBIF (online)) and literature (links to these data are in the list of references). According to Latvian and Ukraine legislation, no additional approvals or permits are required for the studies. According to Latvian legislation, only certified experts (who are certified for working with particular species/groups) can work with the animals.

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

Data Availability Statement: The data were derived from public domain resources. Environmental data: https://www.climond.org/, http://www.earthenv.org/, and https://csidotinfo.wordpress.com/. Occurrence data collection: *Aristichthys nobilis* (Richardson, 1846); *Hypophthalmichthys nobilis*; GBIF.org (accessed on 7 January 2022); GBIF Occurrence Download: https://doi.org/10.15468/dl.rbcrky (accessed on 7 January 2022); *Hypophthalmichthys molitrix* (Valenciennes, 1844); GBIF.org (accessed on 7 January 2022); GBIF Occurrence Download: https://doi.org/10.15468/dl.46yqnd (accessed on 7 January 2022). The data that support the findings of this study are available in the Supplementary Materials of this article.

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References

1. Liao, I.C.; Chao, N.H. Aquaculture and food crisis: Opportunities and constraints. *Asia Pac. J. Clin. Nutr.* **2009**, *18*, 564–569. [PubMed]
2. Neori, A.; Shpige, M.; Guttman, L.; Israel, A. Development of polyculture and integrated multi-trophic aquaculture (IMTA) in Israel: A review. *Isr. J. Aquac.-Bamidgeh* **2017**, *69*, 1–19. [CrossRef]
3. Rakocy, J.E. Aquaponics—Integrating fish and plant culture. In *Aquaculture Production Systems*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012; pp. 344–386. [CrossRef]
4. Billard, R.; Berni, P. Trends in cyprinid polyculture. *Cybium* **2004**, *28*, 255–261.

5. Jeney, Z.; Jian, Z. Use and exchange of aquatic resources relevant for food and aquaculture: Common carp (*Cyprinus carpio* L.). *Rev. Aquac.* **2009**, *1*, 163–173.
6. Woynarovich, A.; Bueno, P.B.; Altan, O.; Jeney, Z.; Reantaso, M.; Xinhua, Y.; Van Anrooy, R. *Better management practices for carp production in Central and Eastern Europe, the Caucasus and Central Asia*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2011.
7. Szücs, I.; Stündl, L.; Váradi, L. Carp farming in Central and Eastern Europe and a case study in multifunctional aquaculture. In *Species and System Selection for Sustainable Aquaculture*; Springer: Berlin/Heidelberg, Germany, 2007; pp. 389–414.
8. Kuybida, V.V.; Nekrasova, O.D.; Kutsokon, Y.K.; Lopatynska, V.V. Summer fish kills in the Kaniv Reservoir. *Hydrobiol. J.* **2019**, *55*, 103–106. [CrossRef]
9. Nekrasova, O.D.; Tytar, V.M.; Kuybida, V.V. *GIS Modeling of Climate Change Vulnerability of Amphibians and Reptiles in Ukraine*; NAS of Ukraine, Shmalgausen Institute of Zoology NAS: Kyiv, Ukraine, 2019; pp. 1–204. ISBN 978-966-02-8956-7. (In Ukrainian)
10. Nekrasova, O.; Tytar, V.; Pupins, M.; Čeirāns, A.; Marushchak, O.; Skute, A. GIS Modeling Study of the Distribution of Viviparous Invasive Alien Fish Species in Eastern Europe in Terms of Global Climate Change, as Exemplified by *Poecilia reticulata* Peters, 1859 and *Gambusia holbrooki* Girarg, 1859. *Diversity* **2021**, *13*, 385. [CrossRef]
11. Tytar, V.; Nekrasova, O.; Pupins, M.; Čeirāns, A.; Skute, A. Modelling the range expansion of pumpkinseed *Lepomis gibbosus* across Europe, with a special focus on Ukraine and Latvia. *North-West. J. Zool.* **2022**, *18*, 143–150.
12. Georges, J.-Y.; Pupins, M.; Nekrasova, O.; Marushchak, O.; Tytar, V.; Skute, A.; Ceirans, A.; Petrov, I.; Garkajs, A.; Theissinger, K. Distribution trends of invasive Asian carps (*Hypophthalmichthys molitrix* and *Aristichthys nobilis*) in Europe in the context of climate change. In Proceedings of the 36th Congress of the International Society of Limnology, Berlin, Germany, 7–10 August 2022; p. 335.
13. Wang, J.; Lamer, J.T.; Gaughan, S.; Wachholtz, M.; Wang, C.; Lu, G. Transcriptomic comparison of invasive bigheaded carps (*Hypophthalmichthys nobilis* and *Hypophthalmichthys molitrix*) and their hybrids. *Ecol. Evol.* **2016**, *6*, 8452–8459. [CrossRef]
14. Karpova, E.P.; Boltachev, A.R. *Fish of the Inner Water Reservoirs in the Crimean Peninsula*; Business-Inform: Simferopol, Crimea, 2012; p. 200.
15. Ayles, G.B.; Campbell, K.; Gillis, D.; Saunders, L.; Scott, K.J.; Tallman, R.; Traverse, N. Technical assessment of the status, health and sustainable harvest levels of the lake Winnipeg fisheries resource. In *Lake Winnipeg Quota Review Task Force Report*, 2nd ed.; Conover, G., Simmonds, R., Whalen, M., Eds.; Asian Carp Working Group, Aquatic Nuisance Species Task Force: Washington, DC, USA, 2011; Volume 3, pp. 154–196.
16. Zambrano, L.; Martínez-Meyer, E.; Menezes, N.; Peterson, A.T. Invasive potential of common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in American freshwater systems. *Can. J. Fish. Aquat. Sci.* **2006**, *63*, 1903–1910. [CrossRef]
17. Milardi, M.; Chapman, D.; Lanzoni, M.; Long, J.M.; Castaldelli, G. First evidence of bighead carp wild recruitment in Western Europe, and its relation to hydrology and temperature. *PLoS ONE* **2017**, *12*, e0189517. [CrossRef]
18. Jawdhari, A.; Mihăilescu, D.F.; Fendrihan, S.; Jujea, V.; Stoilov-Linu, V.; Negrea, B.M. Silver Carp (*Hypophthalmichthys molitrix*) (Asian Silver Carp) Presence in Danube Delta and Romania—A Review with Data on Natural Reproduction. *Life* **2022**, *12*, 1582. [CrossRef]
19. Conover, G.; Simmonds, R.; Whalen, M. Management and control plan for bighead, black, grass, and silver carps in the United States. In *Asian Carp Working Group, Aquatic Nuisance Species Task Force, Eds.*; Asian Carp Working Group, Aquatic Nuisance Species Task Force: Washington, DC, USA, 2007; Volume 3, pp. 154–196.
20. Novitskiy, R.A. Scale, Direction and Consequences of Alien Fish Species Invasions in the Dnieper Reservoirs: Avt. Ph.D. Thesis, Dnipro State Agrarian and Economic University, Kyiv, Ukraine, 2019; p. 41.
21. Ciolac, A. Migration of fishes in Romanian Danube River. *Appl. Ecol. Environ. Res.* **2004**, *2*, 143–163. [CrossRef]
22. Molnár, T.; Lehoczky, I.; Edviné Meleg, E.; Boros, G.; Specziár, A.; Mozsár, A.; Vitál, Z.; Józsa, V.; Allele, W.; Urbányi, B.; et al. Comparison of the Genetic Structure of Invasive Bigheaded Carp (*Hypophthalmichthys* spp.) Populations in Central-European Lacustrine and Riverine Habitats. *Animals* **2021**, *11*, 2018. [CrossRef] [PubMed]
23. Robinson, D.C.E.; Knowler, D.; Kyobe, D.; de la Cueva Bueno, P. *Preliminary Damage Estimates for Selected Invasive Fauna in B.C.*; Report Prepared for Ecosystems Branch; B.C. Ministry of Environment, Victoria, B.C. by ESSA Technologies Ltd.: Vancouver, BC, USA, 2013; p. 62.
24. Pupins, M.; Nekrasova, O.; Marushchak, O.; Tytar, V.; Theissinger, K.; Čeirāns, A.; Skute, A.; Georges, J.-Y. Potential Threat of an Invasive Fish Species for Two Native Newts Inhabiting Wetlands of Europe Vulnerable to Climate Change. *Diversity* **2023**, *15*, 201. [CrossRef]
25. Soes, D.M.; Leuven, R.S.E.W.; Matthews, J.; Broeckx, P.B.; Haenen, O.L.M.; Engelsma, M.Y. A risk analysis of bigheaded carp (Hypophthalmichthys sp.) in the Netherlands. 2011. 118p. Available online: https://repository.ubn.ru.nl/handle/2066/123477 (accessed on 20 April 2024).
26. DeVaney, S.C.; McNyset, K.M.; Williams, J.B.; Peterson, A.T.; Wiley, E.O. A tale of four "carp": Invasion potential and ecological niche modeling. *PLoS ONE* **2009**, *4*, e5451. [CrossRef] [PubMed]
27. Chen, P.; Wiley, E.O.; Mcnyset, K.M. Ecological niche modeling as a predictive tool: Silver and bighead carps in North America. *Biol. Invasions* **2007**, *9*, 43–51. [CrossRef]
28. Kulhanek, S.A.; Leung, B.; Ricciardi, A. Using ecological niche models to predict the abundance and impact of invasive species: Application to the common carp. *Ecol. Appl.* **2011**, *21*, 203–213. [CrossRef] [PubMed]

29. Lübcker, N.; Zengeya, T.A.; Dabrowski, J.; Robertson, M.P. Predicting the potential distribution of invasive silver carp *Hypophthalmichthys molitrix* in South Africa. *Afr. J. Aquat. Sci.* **2014**, *39*, 157–165. [CrossRef]
30. Smith, A. Bigheaded carps (*Hypophthalmichthys molitrix* and *H. nobilis)* An Annotated Bibliography on Literature Composed from 1970 to 2014. Publication 2890. Mississippi State University Extension, 2015. 43 p. Available online: https://extension.msstate.edu/sites/default/files/publications/publications/p2890.pdf (accessed on 4 September 2023).
31. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I.; et al. (Eds.) *IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021; p. 35.
32. *Historical Aquaculture in Northern Europe. Historical Aquaculture in Northern Europe, Eds. Madeleine Bonow, Håkan Olsén and Ingvar Svanberg*; Elanders: Stockholm, Sweden, 2016; p. 204.
33. *Aristichthys nobilis* (Richardson, 1846) (=*Hypophthalmichthys nobilis*) GBIF.org. Available online: https://www.gbif.org/occurrence/download/0097149-210914110416597 (accessed on 7 January 2022).
34. *Hypophthalmichthys molitrix* (Valenciennes, 1844) GBIF.org. Available online: https://www.gbif.org/occurrence/download/0097129-210914110416597 (accessed on 7 January 2022).
35. Osorio-Olvera, L.; Lira-Noriega, A.; Soberón, J.; Peterson, A.T.; Falconi, M.; Contreras-Díaz, R.G. ntbox: An r package with graphical user interface for modelling and evaluating multidimensional ecological niches. *Methods Ecol. Evol.* **2020**, *11*, 1199–1206. [CrossRef]
36. Kriticos, D.J.; Jarošik, V.; Ota, N. Extending the suite of Bioclim variables: A proposed registry system and case study using principal components analysis. *Methods Ecol. Evol.* **2014**, *5*, 956–960. [CrossRef]
37. Domisch, S.; Amatulli, G.; Jetz, W. Near-global freshwater-specific environmental variables for biodiversity analyses in 1 km resolution. *Sci. Data* **2015**, *2*, 150073. [CrossRef]
38. Trabucco, A.; Zomer, R. Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database v2. Figshare. Fileset. Available online: https://figshare.com/articles/dataset/Global_Aridity_Index_and_Potential_Evapotranspiration_ET0_Climate_Database_v2/7504448 (accessed on 4 September 2023).
39. Phillips, S.J. A brief tutorial on Maxent. *ATT Res.* **2005**, *190*, 231–259.
40. Peterson, A.T.; Papes, M.; Soberón, J. Rethinking receiver operating characteristic analysis applications in ecological niche modeling. *Ecol. Model.* **2008**, *213*, 63–72. [CrossRef]
41. Anderson, R.P.; Lew, D.; Peterson, A.T. Evaluating predictive models of species' distributions: Criteria for selecting optimal models. *Ecol. Model.* **2003**, *162*, 211–232. [CrossRef]
42. Fielding, A.H.; Bell, J.F. A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environ. Conserv.* **1997**, *24*, 38–49. [CrossRef]
43. Allouche, O.; Tsoar, A.; Kadmon, R. Assessing the accuracy of species distribution models: Prevalence, Kappa and the True Skill Statistic (TSS). *J. Appl. Ecol.* **2006**, *43*, 1223–1232. [CrossRef]
44. Hammer, Ø.; Harper, D.A.T.; Ryan, P.D. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontol. Electron.* **2001**, *4*, 9. Available online: http://palaeo-electronica.org/2001_1/past/issue1_01.htm (accessed on 29 February 2024).
45. Rubenstein, M.A.; Weiskopf, S.R.; Bertrand, R.; Carter, S.L.; Comte, L.; Eaton, M.J.; Thompson, L.M. Climate change and the global redistribution of biodiversity: Substantial variation in empirical support for expected range shifts. *Environ. Evid.* **2023**, *12*, 1–21. [CrossRef]
46. Colwell, R.K.; Thiago, F. Rangel. Hutchinson's duality: The once and future niche. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 19651–19658. [CrossRef]
47. Broennimann, O.; Treier, U.A.; Müller-Schärer, H.; Thiuller, W.; Peterson, A.T.; Giusan, A. Evidence of climatic niche shift during biological invasion. *Ecol. Lett.* **2007**, *10*, 701–709. [CrossRef]