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River networks as ecological hotspots and corridors for invasive and aquaculture species: long-term bioclimatic modeling in Latvia

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Abstract — Climate change significantly affects aquatic biodiversity, particularly through the expansion of invasive species, which pose critical threats to native ecosystems and economic sectors such as aquaculture. This study synthesizes research findings on the impact of climate change-driven species distribution, focusing on three alien thermophilic fish species: silver carp *Hypophthalmichthys molitrix*, bighead carp *Aristichthys nobilis*, and pumpkinseed *Lepomis gibbosus*.

The range expansion of this species has continued across the Europe. Using a species distribution modelling approach, predictions are made of the geographic range of the fish based on presence records and environmental variables from the Near-global environmental information for freshwater ecosystems database likely to be associated with habitat suitability and important for the possible further expansion of the species.

The results show a possible widespread under the current climate situation and prospects for the future expansion of the species under the influence of climate change in Latvian river networks, identifying ecological hotspots and corridors for these invasive and aquaculture species.

In the aquaculture sector, climate change influences the viability of farming conditions and fosters the proliferation of invasive species that compete with or prey upon economically valuable fish stocks. Research on ecological and socioeconomic thresholds in Latvian pond aquaculture underscores the need for adaptive management strategies to mitigate climate-related risks.

These findings underscore the necessity for targeted conservation policies, improved invasive species management, and climate-adaptive strategies in aquaculture. Proactive measures, including habitat restoration, stricter biosecurity regulations, and public awareness campaigns, are essential to mitigate the adverse effects of climate change on biodiversity and economic sustainability.

Keywords— bioclimatic long-term modeling, ecological hotspots and corridors, invasive and aquaculture species, river networks

I. INTRODUCTION

Species dispersal beyond native ranges drives global change, with globalization accelerating organism translocation [1]. Climate change further influences invasion success by enabling range shifts, allowing non-

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native species to establish and outcompete natives under new conditions [2] – [4]. Such shifts can disrupt ecosystems, reducing biodiversity and ecosystem services [5], [6].

Freshwater ecosystems are particularly vulnerable to biological invasions [7], with introduced fish species posing significant threats [8]. In Europe, at least 40 alien fish species have established populations [9]. One such species, the North American sunfish *Lepomis gibbosus*, introduced in the late 19th century, is now widespread across Europe and Asia Minor, with climate change expected to facilitate its northward expansion [10] – [12]. Despite over a century since its introduction, *L. gibbosus* continues to spread [13]. Identifying environmental factors influencing its expansion is crucial for risk assessment and monitoring, particularly in Latvia, where suitable conditions exist but the species is not yet recorded [14].

Species distribution models (SDMs) or ecological niche models (ENMs) predict potential species distributions by correlating presence records with environmental factors [15]. These models, employing statistical and machine learning algorithms, aid in forecasting range expansions under climate change. Similarly, Asian carps pose ecological concerns due to their voracious feeding, which can displace native fish and impact aquatic vegetation. In some areas, they dominate biomass (MICRA 2002), potentially affecting native herpetofauna like the European pond turtle *Emys orbicularis* and amphibians. While some suggest they help control algal blooms, a comprehensive impact assessment is needed [16] – [18].

GIS modeling and ecological niche models are essential for studying fish invasions, yet existing research primarily focuses on other regions or species e.g. *Hypophthalmichthys molitrix* and *Aristichthys nobilis* [19]–[23]. Applying these tools enhances predictions of invasive species spread, informing biodiversity conservation and management strategies.

II. MATERIALS AND METHODS

Occurrence Data Collection

The Ukrainian example was used to obtain data where it was more accessible and then adapted to the Latvian situation. Species occurrence data were sourced from GBIF (2021) [24], FishBase (2022) [25], and social media platforms (Facebook, Twitter, Instagram, Flickr) for Ukraine, utilizing geotagged photos and text-based records [26], [27]. Search queries included Latin and vernacular names in Ukrainian and Russian. Data were compiled for 17 Ukrainian regions, verified using literature sources [28] – [30], and filtered for spatial bias using the 'spThin' R package [31] to maintain a minimum separation distance, reducing autocorrelation [32].

Environmental Data

Environmental variables were sourced from Near-global freshwater ecosystem datasets [33] and the CliMond dataset [34]. Highly correlated variables ($|r| > 0.8$, $p < 0.001$) were removed using the 'caret' R package

[35], and feature selection was performed with the 'Boruta' algorithm [36]. Pseudo-absence points were generated using the 'dismo' package [37].

Model Building

Species distribution models (SDMs) were developed using Maxent [38] and Bayesian additive regression trees (BART) [39]. Response curves were analyzed to assess variable effects on habitat suitability [40]. Maxent models were optimized using the 'SDMtune' package [41], adjusting feature classes and regularization multipliers [42]. The 10th percentile training presence threshold was used for habitat suitability delineation [43]. Considering niche differences between native and invaded ranges [44], we compared bioclimatic niches using ANOSIM [45]. Maps were processed in SAGA GIS [46], and statistical analyses were performed using PAST [47].

This approach integrates GIS modeling and SDMs to assess the feasibility and environmental suitability of invasive species expansion in Latvia, with implications for conservation and aquaculture management.

III. RESULTS AND DISCUSSIONS

When looking at possible future climate scenarios for Latvia, seasonality has great importance. Comparing the average temperatures and precipitation values of the recent past (1961–1990) and the future (2071–2100) months, it can be clearly seen that higher air temperatures are expected in all months in the future than today (see the example of the Latvia town Dobeles) (Figure 1). More precipitation is expected in most of the year in the future, only in April and July–September there will be less precipitation. Winter will become three months shorter. Only in one of the coldest months of the year (February) the average air temperature will be below zero. Spring will come in March two weeks earlier than today and will be shorter. In May of the future, the weather conditions will correspond to today's June. Summer will become two months longer, and in addition, temperatures typical of today's hottest months (July, August) are expected in June and September, but July and August in the future will be significantly – on average by four degrees – hotter than today. The summer months of June–August will be the wettest, just like today, while the “new” summer month of September will be dry (like today's May). Weather conditions similar to today's autumn (October–November) will prevail for three months – from November to January. The long autumn will be made particularly unpleasant by a third more frequent rains

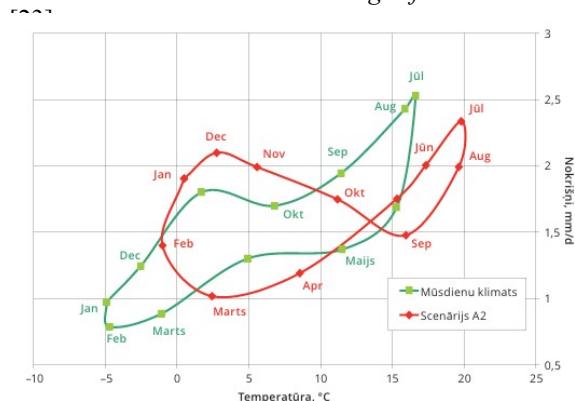


Fig. 1. Temperature-precipitation diagram for current and future climate (IPCC scenario A2) in Dobeles [48]

These temperature changes create a favorable environment for invasive alien crustacean species, the arrival of which is associated with both deliberate introduction and secondary spread after their invasion into European freshwaters. The alien crustacean species found in Latvian freshwaters are mainly North American and Ponto-Caspian species, whose arrival is associated with both deliberate introduction and secondary spread after their invasion into European freshwaters. The large decapod – the American signal crayfish – was introduced to Latvia for the purpose of scientific experiments in 1983 in one lake [49], but in later years and currently occurs in the Salaca and Gauja river basins [50]. The other North American species – the American spinycheek crayfish (*Faxonius limosus*) – is a more recent arrival, first detected in the territory of Latvia in 2005 in the Lielupe River [51]. It was first introduced into European freshwaters in Germany in 1890 and has since been introduced into German, Polish and French waters [52]. In Latvia, it is currently found in the Venta, Lielupe and Daugava river basins [50]. The Ponto-Caspian decapod, the narrow-clawed crayfish (*Astacus leptodactylus*), was observed in Latvian freshwaters already at the beginning of the 20th century, and its occurrence is currently associated mainly with the freshwaters of Vidzeme and Zemgale [49]. Representatives of another group of alien crustaceans of the Ponto-Caspian region, Amphipoda, which are widespread in European waters, are found in Latvian freshwaters – mainly *Pontogammaridae* and *Gammaridae* families [53]. Certain amphipods *Obesogammarus crassus* and *Dikerogammarus villosus* are already potential newcomers to Latvian freshwaters, as they have been found in Latvian ports and the Daugava estuary [54], [55]. In turn, *Ponto gammarus robustoides* is much more widely distributed in Latvian freshwaters, as it was purposefully introduced in the 1960s to improve the fish food base in the Great Baltezers and the Kegums Reservoir together with other species of the Ponto-Caspian region – the amphipoda *Chaetogammarus warpachowskyi* and the mysids *Paramysis lacustris*, *Limnomysis benedeni*. Further studies showed that *P. lacustris* has settled best in the

Environment. Technology. Resources. Rzekne, Latvia
 new habitats in the near Riga lakes and *P. robustoides* in the Kegums Reservoir [56], [57]. Currently, the amphipoda *P. robustoides* is found in the mouth of the Daugava River and its lower reaches in the Riga, Kegums and Pļaviņas reservoirs, as well as in the Latvian coastal lakes (Papes, Liepājas, Babītes, Lilastes, etc.), as well as in the tributaries of the large and small rivers of the Baltic Sea and the Gulf of Riga, such as Lielupe, Saka, Venta, Roja, Aģe, Ķīšupe, etc. or in their mouths [58], [59]. This can be explained not only by introduction, but also by the secondary spread of the species in the Baltic Sea after introduction into the freshwaters of Lithuania and/or Latvia [60]. Recent studies have revealed that the alien amphipoda *P. robustoides* is common in the lower reaches of the Daugava and, continuing its spread, has already established itself upstream of the Pļaviņa Reservoir (Figure 2) [58].

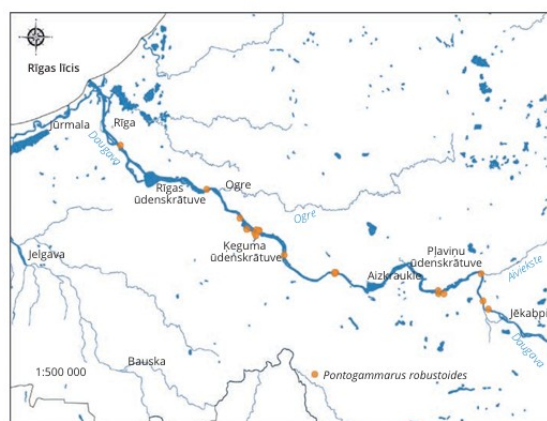


Fig. 2. Occurrence of the alien amphipods *P. robustoides* in the lower reaches of the Daugava River [55],[58].

In the lower reaches of the Daugava, *P. robustoides* has become the dominant amphipod. The native amphipod *Gammarus pulex* was found in the Kegums Reservoir at the mouth of the Rītupīte stream and upstream of the Pļaviņa Reservoir near Zelķi between the amphipods *P. robustoides* and *G. varsoviensis*, which according to the latest research data is also considered a Ponto-Caspian amphipod [61]. In fact, *P. robustoides* has outcompeted and replaced the local amphipod *G. pulex* in the lower Daugava, as this species was present in the lower Daugava in studies of the 1960s [62], and has also affected the diversity of invertebrate species. In places with a higher number of *P. robustoides* individuals, a decrease in species diversity is observed (Figure 3).

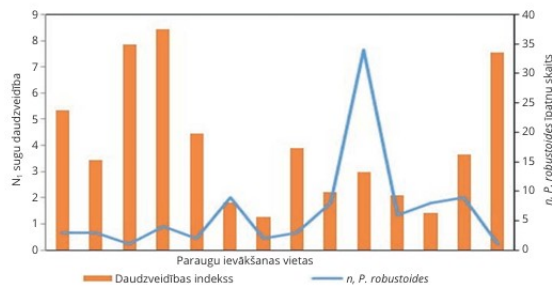


Fig. 3. Number of individuals of the alien side-swimming *P. robustoides* versus species diversity N1 (the value of N1 depends on the number of individuals of the species: the greater the number of individuals of a species, the lower the diversity) [48].

A similar trend is also observed for the previously discussed species *L.gibbosus*, whose distribution map was created in the study conducted. The obtained probability maps were averaged to produce a habitat suitability map for the pumpkinseed corresponding to the current climate in Europe and clipped to and Latvia (Figure 4). Contour lines distinguishing suitable for the species areas match the 10th percentile training presence threshold value [14].

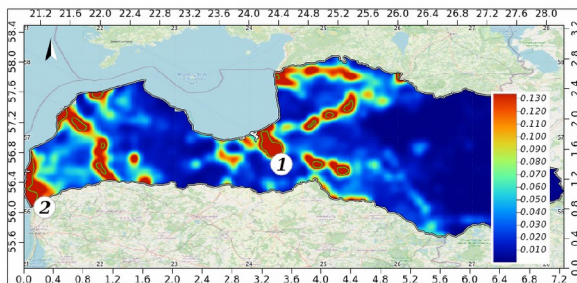


Fig. 4. Map of predicted habitat suitability for the pumpkinseed in Latvia based on the combination of selected predictors from the Near-global environmental information for freshwater ecosystems; the legend shows habitat suitability ranging from relatively high (red) to low (blue); areas suggested for legal introduction: 1 - Lower Daugava, 2 - Kurzeme Province [14].

Also 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 [63].

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 5). This expansion will encompass

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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 5).

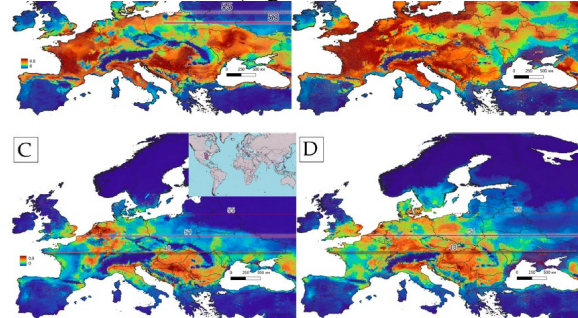


Fig. 5. Potential (probabilistic) model of Asian carp expansion built in the Maxent program in Europe based on CliMond dataset (red color > 0.5). *H.molitrix*: (A) current (dotted line marks - 55° N, red line marks - 53° N); (B) CliMond dataset 2050 (thin line - 62° N, thick red line - 58° N). *A.nobilis* (dotted line - 55° N; thin line - 51° N, thick red line - 48° N); (C) current; (D) CliMond dataset 2050 [14].

These findings corroborate former studies reporting that most thermophilic freshwater animals are likely to experience range shifts in the future [16], [63], [64]. According to former forecasts, self-reproduction of silver carps will likely occur in the Netherlands by 2050 [23]. 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.

IV. CONCLUSIONS

Our research highlights river networks as ecological hotspots and corridors for invasive and aquaculture species, emphasizing the northward expansion of Asian carps in response to climate change. By 2050, Northern European waters will likely provide suitable conditions for these species, necessitating proactive management strategies to mitigate ecological risks while harnessing potential aquaculture benefits.

By analyzing 598 occurrence records in Europe and 873 in North America, we identified 18 key environmental variables influencing species distribution, with temperature playing a critical role. The climatic predictor 'tmin9' (minimum monthly air temperature in September) was particularly significant, closely correlating with temperatures during the growing season [65]. Our models confirm that polycultures of Asian carps can thrive, enhancing their adaptability to extreme conditions, but also posing a significant challenge to native biodiversity. Experimental and field-based studies [66], [67] have shown that species such as *L. gibbosus* require water temperatures above 9.5 °C to feed actively, reinforcing the importance of temperature in species distribution.

Effective management requires:

- Impact assessments to evaluate ecological risks, including potential disease spread [68], [69].
- Monitoring and control strategies to prevent uncontrolled expansion [70], [71].
- Collaboration among scientists, policymakers, and stakeholders to balance aquaculture development with biodiversity conservation [72].

Our modeling also indicates that Latvia has a low probability of spontaneous invasion by *L. gibbosus*, with only 3% of the country offering moderate suitability. However, coastal areas and the Lower Daugava could become viable habitats under warming conditions. Historical data show that *L. gibbosus* spread rapidly through Ukrainian river systems, aided by reservoirs and human activities [73], [30]. While GIS-based species distribution models (SDMs) provide valuable insights, ongoing field validation is essential to refine predictions and inform sustainable management policies [75].

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