Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume I, 305-311

River Networks as Ecological Hotspots and Corridors for Invasive and Aquaculture Species: Long-Term Bioclimatic Modeling in Latvia

Liega Krasovska
Department of Ecology
Daugavpils University
Daugavpils, Latvia
liegakrasovska@inbox.lv

Mihails Pupins
Department of Ecology
Daugavpils University
Daugavpils, Latvia
mihails.pupins@gmail.com

Andris Čeirāns
Department of Ecology
Daugavpils University
Daugavpils, Latvia
cuskisa@gmail.com

Arturs Škute
Department of Ecology
Daugavpils University
Daugavpils, Latvia
arturs.skute@du.lv

Volodymyr Tytar
Schmalhausen Institute of Zoology
National Academy of Sciences of Ukraine
Kyiv, Ukraine
vtytar@gmail.com

Oksana Nekrasova
CNRS, IPHC UMR 7178, Université de Strasbourg, Strasbourg, France, Department of Ecology, Daugavpils University
Daugavpils Latvia,
Schmalhausen Institute of Zoology National Academy of Sciences of Ukraine,
Kyiv, Ukraine
oneks22@gmail.com

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

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol1.8703

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

A. *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].

B. *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].

C. *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 Dobele) (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 [23].

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].

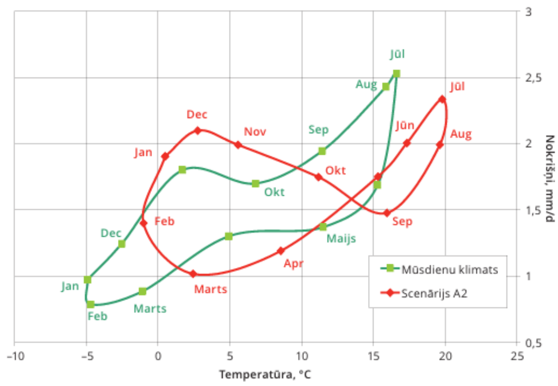

Fig. 1. Temperature-precipitation diagram for current and future climate (IPCC scenario A2) in Dobele [48].

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]. 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 new habitats in the near Riga lakes and *P. robustoides* in the Kegums Reservoir [55], [56]. Currently, the amphipoda *P. robustoides* is found in the mouth of the Daugava River and its lower reaches in the Riga, Ķegums 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 [57], [58]. 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 [59], [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].

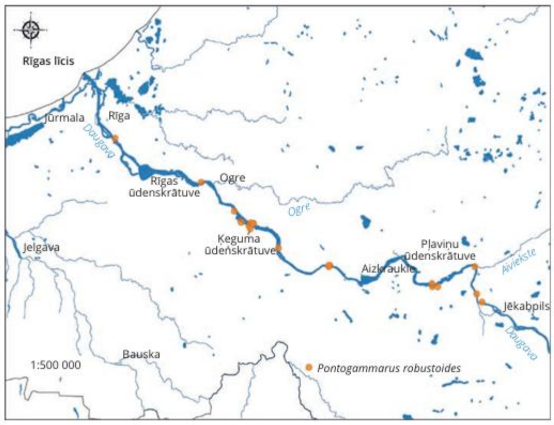

Fig. 2. Occurrence of the alien amphipods *P. robustoides* in the lower reaches of the Daugava River [55],[58].

In the lower reaches of the Daugava, *P. robustoides* has become the dominant amphipod. The native amphipod *Gammarus pulex* was found in the Ķegums Reservoir at the mouth of the Rītupīte stream and upstream of the Pļaviņa Reservoir near Zeļķi 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).

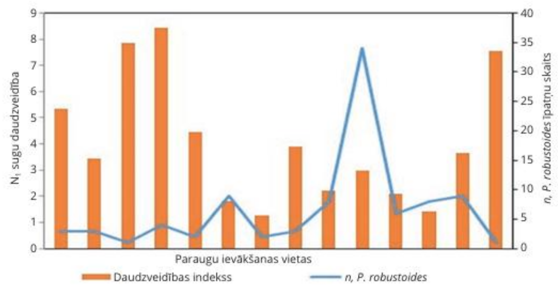

Fig. 3. Number of individuals of the alien side-swimming *P. robustoides* versus species diversity N1 (the value of N1 depends on the number of individuals of the species: the greater the number of individuals of a species, the lower the diversity) [48].

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].

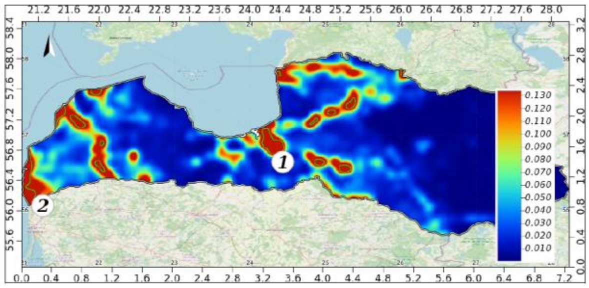

Fig. 4. Map of predicted habitat suitability for the pumpkinseed in Latvia based on the combination of selected predictors from the Near-global environmental information for freshwater ecosystems; the legend shows habitat suitability ranging from relatively high (red) to low (blue); areas suggested for 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 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).

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.

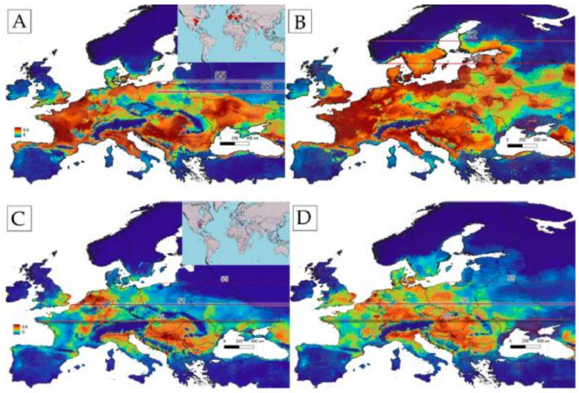

Fig. 5. Potential (probabilistic) model of Asian carp expansion built in the Maxent program in Europe based on CliMond dataset (red color > 0.5). *H.molitrix*: (**A**) current (dotted line marks - 55° N, red line marks – 53° N); (**B**) CliMond dataset 2050 (thin line – 62° N, thick red line – 58° N).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

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 modelling 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].

V. Acknowledgments

We acknowledge the Emys-R project (https://emysr.cnrs.fr) funded through the 2020–2021 Biodiversa + and Water JPI joint call for research projects, under the BiodivRestore ERA-NET Cofund (GA N°101003777), with the EU and the funding organizations Agence Nationale de la Recherche (ANR, France, grant ANR-21-BIRE-0005), Bundesminis- terium für Bildung und Forschung (BMBF, Germany, grant 16LW015), Latvijas Zinātnes padome, LZP (Latvian Council of Science) (LZP, grant ES RTD/2022/2), and the National Science Center (NSC, Poland, grant 2021/03/Y/NZ8/00101). We are also thankful for the support from the Collège de France and Agence Nationale de la Recherche (ANR) through the PAUSE ANR Ukraine program (Nekrasova O., grant ANR-23-PAUK- 0074), and the project "Ecological and socioeconomic thresholds as a basis for defining adaptive management triggers in Latvian pond aquaculture" (lzp-2021/1–0247), project 16–00-F02201–000002 for the use of the mobile complex of scientific laboratories for research purposes.

References

[1] R. Early, B. Bradley, J. Dukes, J.J. Lawler, J.D. Olden, D.M. Blumenthal, P. Gonzalez, E.D. Grosholz, I. Ibañez, L.P. Miller, C.J.B. Sorte, and A.J. Tatem, "Global threats from invasive alien species in the twenty-first century and national response capacities," Nature Communications 7: 12485, 2016.

[2] G.R. Walther, A. Roques, P.E. Hulme, M.T. Sykes, P. Pyšek, I. Kühn, M. Zobel, S. Bacher, S. Botta-Dukát, H. Bugmann, B. Czúcz, J. Dauber, T. Hickler, V. Jarošík, M. Kenis, S. Klotz, D. Minchin, M. Moora, W. Nentwig, J. Ott, V.E. Panov, B. Reineking, C. Robinet, V. Semenchenko, W. Solarz, W. Thuiller, M. Vilà, K. Vohland, J. Settele, "Alien species in a warmer world: risks and opportunities," Trends in Ecology & Evolution 24(12), 2009, pp. 686-693.

[3] D. Fletcher, "Biological invasion risk assessment, considering adaptation at multiple scale: The case of topmouth gudgeon Pseudorasbora parva," Thesis University of Montpellier, 2018, 215 pp.

[4] J.S. Dukes, and H.A. Mooney, "Does global change increase the success of biological invaders?" Trends in Ecology & Evolution, vol. 14(4), 1999, pp.135-139.

[5] O. Schweiger, J.C. Biesmeijer, R. Bommarco, T. Hickler, P.E. Hulme, S. Klotz., I. Kühn, M. Moora, A. Nielsen, R. Ohlemüller, T. Petanidou, S.G. Potts, P. Pyšek, J.C. Stout, M.T. Sykes, T. Tscheulin, M. Vilà, G.R. Walther, C. Westphal, M. Winter, M. Zobel, J. Settele, "Multiple stressors on biotic interactions: how climate change and alien species interact to affect pollination," Biological Reviews 85(4), 2010, pp. 777-795.

[6] V.V. Kuybida, O.D. Nekrasova, Y.K. Kutsokon, V.V. Lopatynska, "Summer fish kills in the Kaniv Reservoir," Hydrobiological Journal 55(1), 2019, pp. 103–106.

[7] T.P. Moorhouse, and D.W. Macdonald, "Are invasives worse in freshwater than terrestrial ecosystems?" WIREs Water 2, 2015, pp. 1-8.

[8] G.H. Copp, J.R. Britton, Z. Guo, V. Ronni Edmonds-Brown, J. Pegg, L. Vilizzi, P.I. Davison, "Trophic consequences of non-native pumpkinseed *Lepomis gibbosus* for native pond fishes," Biological Invasions 19, 2017, pp. 25-41.

[9] G. Van Der Veer, W. Nentwig, "Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system," Ecology of Freshwater Fish 24, 2015, pp. 646-656

[10] G.H. Copp, M.G. Fox, "Growth and life history traits of introduced pumpkinseed (*Lepomis gibbosus*) in Europe, and the relevance to invasiveness potential," Gherardi, F. (ed.), Freshwater bioinvaders: profiles, distribution, and threats, Springer, Berlin, 2007, pp. 289-306.

[11] F.J. Rahel, J.D. Olden, "Assessing the effects of climate change on aquatic invasive species," Conservation Biology 22(3), 2008, pp. 521-533.

[12] J.R. Britton, J. Cucherousset, G.D. Davies, M.J. Godard, G.H. Copp, "Non-native fishes and climate change: predicting species responses to warming temperatures in a temperate region," Freshwater Biology 55, 2010, pp. 1130-1141.

[13] S. Yavno, J. Gobin, C.C. Wilson, A. Vila-Gispert, G.H. Copp, M.G. Fox, "New and Old World phylogeography of pumpkinseed *Lepomis gibbosus* (Linnaeus, 1758): the North American origin of introduced populations in Europe," Hydrobiologia 847, 2020, pp. 345-364.

[14] V.M. Tytar, O.D. Nekrasova, M. Pupins, A. Čeirāns, A. Skute, "Modelling the range expansion of pumpkinseed Lepomis gibbosus across Europe, with special focus on Latvia and Ukraine," Zhorov, D.G., Buga, S.V., Semenchenko, V.P., Petrašiūnas, D.A., Kolbas, A.P., Adamovich, B.V., Sinchuk, A.V.

(eds.), Book of Abstracts of the 1st International Scientific Conference: «Alien species of animals, fungi and plants in Belarus and neighboring countries», Minsk, Belarus, March 23, 2021, Belarusian State University, 2021, pp. 112.

[15] O.D. Nekrasova, V.M. Tytar, V.V. Kuybida, "GIS modeling of climate change vulnerability of amphibians and reptiles in Ukraine," NAS of Ukraine, Shmalgausen Institute of Zoology NAS, Kyiv, Ukraine, [in Ukrainian], 2019.

[16] J.Y. Georges, M. Pupins, O. Nekrasova, O. Marushchak, v. Tytar, A. Skute, A. Ceirans, I. Petrov, A. Garkajs, K. Theissinger, "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; pp. 335.

[17] D.C.E. Robinson, D.Knowler, D. Kyobe, P. de la Cueva Bueno, "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, pp. 62.

[18] D.M. Soes, R.S.E.W. Leuven, J. Matthews, P.B. Broeckx, O.L.M. Haenen, M.Y. Engelsma, "A risk analysis of bigheaded carp (*Hypophthalmichthys sp.*) in the Netherlands," 2011, pp 118. [Online]. Available: https://repository.ubn.ru.nl/handle/2066/123477 [Accessed: April 20, 2024].

[19] S.C. DeVaney, K.M. McNyset, J.B. Williams, A.T. Peterson, E.O. Wiley, "A tale of four "carp": Invasion potential and ecological niche modeling," PLoS ONE, 4, e5451, 2009.

[20] P. Chen, E.O. Wiley, K.M. Mcnyset, "Ecological niche modeling as a predictive tool: Silver and bighead carps in North America," Biol. Invasions, 9, 2007, pp. 43–51.

[21] S.A. Kulhanek, B. Leung, A. Ricciardi, "Using ecological niche models to predict the abundance and impact of invasive species: Application to the common carp," Ecol. Appl., 21, 2011, pp. 203–213.

[22] N. Lübcker, T.A. Zengeya, J. Dabrowski, M.P. Robertson, "Predicting the potential distribution of invasive silver carp *Hypophthalmichthys molitrix* in South Africa," Afr. J. Aquat. Sci., 39, 2014, pp. 157–165.

[23] A. Smith, "Bigheaded carps (*Hypophthalmichthys molitrix* and *H. nobilis*)," An Annotated bibliography on literature Composed from 1970 to 2014, publication 2890, Mississippi State University extension, 2015, pp. 43. [Online] Available: https://extension.msstate.edu/sites/default/files/publications/publications/p2890.pdf [Accessed: Sept. 4, 2023].

[24] GBIF, "*Lepomis gibbosus* (Linnaeus, 1758)," 2021. [Online] Avalaible: https://doi.org/10.15468/dl.599axj [Accessed: May 4, 2021].

[25] R. Froese, D. Pauly, "FishBase," 2022. [Online] Avalaible: www.fishbase.org [Accessed: Jun. 6, 2022].

[26] T. Toivonen, V. Heikinheimo, C. Fink, A. Hausmann, T. Hiippala, O. Järv, H. Tenkanen, E. Di Minin, "Social media data for conservation science: A methodological overview," Biological Conservation, 233, 2019, pp. 298-315.

[27] O. Nekrasova, V. Tytar, M. Pupins, A. Čeirāns, "Range expansion of the alien red-eared slider *Trachemys scripta* (*Reptilia*, *Testudines*) in Eastern Europe, with special reference to Latvia and Ukraine," BioInvasions Records 11(1), 2022, pp. 287–295.

[28] L.S. Berg, "The freshwater fishes of the USSR and adjacent countries," 4th ed., Part 3. Academia Nauk USSR, Moscow & Leningrad [in Russian], 1949, pp. 927-1382.

[29] O.A. Diripasko, N.A. Demchenko, P.V. Kulik, T.A. Zabroda, "An Expansion of the Pumpkinseed, *Lepomis gibbosus* (*Centrarchidae, Perciformes*) Area of Distribution into the East of Ukraine," Vestnik Zoologii 42(3), 2008, pp. 269-273.

[30] E.V. Fedonenko, O.N. Marenkov, "Spreading, spatial distribution, and morphometric characteristics of the pumpkinseed sunfish *Lepomis gibbosus* (*Centrarchidae, Perciformes*) in the Zaporozhye Reservoir," Russian Journal of Biological Invasions 4(3), 2013, pp. 194-199.

[31] M.E. Aiello-Lammens, R.A. Boria, A. Radosavljevic, B. Vilela, R.P. Anderson, "spThin: an R package for spatial thinning of species occurrence records for use in ecological niche models," Ecography 38(5), 2015, pp 541-545.

[32] J.W. Lichstein, T.R. Simons, S.A. Shriner, K.E. Franzreb, "Spatial autocorrelation and autoregressive models in ecology," Ecological Monographs 72(3), 2002, pp. 445-463.

[33] S. Domisch, G. Amatulli, W. Jetz, "Near-global freshwater-specific environmental variables for biodiversity analyses in 1 km resolution," Scientific Data 2:150073, 2015.

[34] S.E. Fick, R.J. Hijmans, "WorldClim 2: new 1 - km spatial resolution climate surfaces for global land areas," International Journal of Climatology 37, 2017, pp. 4302-4315.

[35] M. Kuhn, "Building Predictive Models in R Using the caret Package," Journal of Statistical Software 28(5), 2008, pp. 1-26.

[36] M.B. Kursa, A. Jankowski, W.R. Rudnicki, "Boruta - A system for Feature Selection. Fundamenta Informaticae 101, 2010, pp. 271-285.

[37] R.J. Hijmans, S. Phillips, J. Leathwick, J.Elith, "Package 'dismo'," 2011. [Online] Available: http://cran.r-project.org/web/packages/dismo/ index.html [Accessed: February 20, 2025].

[38] S.J. Phillips, R.P. Anderson, R.E. Schapire, "Maximum entropy modeling of species geographic distributions," Ecological Modelling 190(3-4), 2006, pp. 231-259.

[39] C.J. Carlson, "Species distribution modelling with Bayesian additive regression trees in R. Methods in Ecology and Evolution," Early View: 1-9. 1584-9074, 2020.

[40] R.A. Baldwin, "Use of maximum entropy modeling in wildlife research," Entropy 11(4), 2009, pp. 854-866.

[41] S. Vignali, A.G. Barras, R. Arlettaz, V. Braunisch, "SDMtune: An R package to tune and evaluate species distribution models," Ecology and Evolution 10(20): 11488-11506, 2020.

[42] C. Merow, M.J. Smith, J.A. Silander Jr, "A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter," Ecography 36(10), 2013, pp. 1058-1069.

[43] S.J. Phillips, M. Dudík, "Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation," Ecography 31(2), 2008, pp. 161-175.

[44] A.T. Peterson, J. Soberón, V. Sánchez-Cordero, "Conservatism of ecological niches in evolutionary time," Science 285, 1999, pp. 1265-1267.

[45] J. Oksanen, F.G. Blanchet, M. Friendly, R. Kindt, P. Legendre, D. McGlinn, P.R. Minchin, R.B. O'Hara, G.L.Simpson, P. Solymos, M.H.H. Stevens, E. Szoecs, H. Wagner, "Vegan: Community ecology package. R package version 2.5-3.," 2018. [Online] Avalaible: http://CRAN.R-project.org/package=vegan [Accessed: Feb. 20, 2025].

[46] O. Conrad, B. Bechtel, M. Bock, H. Dietrich, E. Fischer, L. Gerlitz, J. Wehberg, V. Wichmann, J. Böhner, "System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. Geoscientific Model Development 8: 1991-2007," 2014.

[47] Ø. Hammer, D.A.T. Harper, P.D. Ryan, "PAST: Paleontological statistics software package for education and data analysis," Palaeontologia Electronica 4(1), 2001, pp. 1-9.

[48] J. Aigars, "Latvijas ekosistēmu dinamika klimata ietekmē," Daugavpils Universitātes aģentūra "Latvijas Hidroekoloģijas institūts", 2018, pp. 114.

[49] T. Taugbøl, A. Arens, A. Mitans, "Freshwater Crayfish in Latvia: Status and Recommendations for Conservation and Sustainable Use," Norwegian Institute for Nature Research, Latvian Crayfish and Fish Farmers Association and Latvian Fisheries Research Institute, NINA Project Report, 2004, pp 29.

[50] J. Birzaks, A. Škute, "Alien crayfish species in Latvian inland waters," Environmental and Experimental Biology, Volume 17, 2019, pp. 21–25.

[51] Ē. Aleksejevs, "Latvijas vēži," Latvijas zivsaimniecības gadagrāmata, 2006, pp. 73-81.

[52] D.M. Holdich, J. Black, "The spinycheek crayfish, *Orconectes limosus* (Rafines que, 1817) [Crustacea: Decapoda: Cambaridae], digs into the UK," Aquatic Invasion, 2, 2007, pp. 1–16.

[53] A. Bij de Vaate, K. Jazdzewski, H.A.M. Ketelaars, S. Gollasch, G. van der Velde, "Geographical patterns in range extension of PontoCaspian macro inver tebrate species in Europe," Canadian Journal of Fisheries and Aquatic Sciences, 59, 2002 pp. 1159–1174.

[54] D. Minchin, K. Arbačiauskas, D. Daunys, E. Ezhova, N. Grudule, J. Kotta, N.Molchanova, S. Olenin, G.Višinskienė, S. Strake, "How far and how fast will the 'killer shrimp' *Dikerogammarus villosus* expand within Baltic coastal and inland waters?", 2018.

[55] I. Dimante-Deimantovica A. Skute, R. Skute, "Vertical variability of pelagic zooplankton fauna in deep Latvian lakes, with some notes on changes in ecological conditions," Estonian Journal of Ecology, 2012, pp 247 – 264.

[56] O.L. Kachalova, G.S. Lagzdin, "Acclimatization of mysids in water bodies of Latvian SSR," Limnology, Proceedings of XIV conference on studies of the inland waters of Baltic States, 3 (1), 1968, pp. 79–82.

[57] V. Bodniece, "Changes in perch food composition related to acclimatization of new food items in the Kegums Water Reservoir," Ecological and biological studies of aquatic animals, Riga, 1968, pp. 25–34.

[58] J. Paidere, A. Brakovska, A.Škute, A. "Ponto-Caspian gammarid *Pontogammarus robustoides* G. O. Sars, 1894 in the Daugava River reservoirs (Latvia)," Zoology and Ecology, 26(3), 2016, pp. 227–235.

[59] N. Grudule, E. Parele, K. Arbačiauskas, "Distribution of PontoCaspian amphipod *Pontogammarus robustoides* in Latvian waters," Acta Zoologica Lituanica 17(1), 2007, pp. 28–32.

[60] K. Arbačiauskas, S. Gumuliauskaitė, "Invasion of the Baltic Sea basin by the PontoCaspian amphipod *Pontogammarus robustoides* and its ecological impact," Biological invaders in inland waters: profiles, distribution, and threats, 2007, pp. 463–477.

[61] M. Grabowski, T. Rewicz, K. BacelaSpychalska, A. Konopacka, T. Mamos, K. Jazdzewski, "Cryptic invasion of Baltic lowlands by freshwater amphipod of Pontic origin," Aquatic Invasion, 7 (3), 2012, pp. 337–346.

[62] J.A. Kumsare, L.O. Kachalova, J.R. Laganovskaja, G.A. Melberga, "Hydro biological and sanitary characteristics of the estuary area of the Daugava," Latvijas PSR Zinātņu Akadēmijas Vēstis, Nr. 5 (238), 1967, pp. 96–104.

[63] O. Nekrasova, M. Pupins, V. Tytar, L. Fedorenko, O. Potrokhov, A. Skute, A.Ceirāns, K. Theissinger, J.Y. Georges, "Assessing Prospects of Integrating Asian Carp Polyculture in Europe: A Nature-Based Solution under Climate Change?" Fishes, 9, 148, 2024.

[64] A. Čeirāns, E. Gravele, I. Gavarane, M. Pupins, L. Mezaraupe, I. Rubenina, Y. Kvach, A. Skute, O. Oskyrko, O.Nekrasova, O. Marushchak, M. Kirjusina, "Helminth communities in amphibians from Latvia with an emphasis on their connection to host ecology,"Journal of Helminthology, 2021.

[65] H.G. Stefan, E.B. Preud'homme, "Stream temperature estimation from air temperature," Journal of the American Water Resources Association 29 (1), 1993, pp. 27-45.

[66] A. Keast, "Feeding of some Great Lakes fishes at low temperatures," Journal of the Fisheries Research Board of Canada 25(6), 1968, pp. 1199-1218.

[67] H.C. Marcus, "The extent to which temperature changes influence-food consumption in large-mouth bass (Iluro floridana)," Transactions of the American Fisheries Society 62, 1932, pp. 202-210.

[68] S.Kumar, S.A. Spaulding, T.J. Stohlgren, K.A. Hermann, T.S. Schmidt, L.L. Bahls, "Potential habitat distribution for the freshwater diatom *Didymosphenia geminata* in the continental US," Frontiers in Ecology and the Environment 7(8), 2009, pp. 415-420.

[69] J.R. Milanovich, W.E. Peterman, N.P. Nibbelink, J.C. Maerz, "Projected loss of a salamander diversity hotspot as a consequence of projected global climate change," Plos One 5(8), 2010, pp. 12-189.

[70] S.J. Wenger, D.J. Isaak, C.H. Luce, H.M. Nevillea, K.D. Fauschc, J.B. Dunhamd, D.C. Dauwalter, M.K.Young, M.M. Elsner, B.E.Rieman, A.F. Hamlet, J.E.Williamsh, "Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change," Proceedings of the National Academy of Sciences of the United States of America 108(34), 2011.

[71] L.Blank, L.Blaustein, "Using ecological niche modeling to predict the distributions of two endangered amphibian species in aquatic breeding sites," Hydrobiologia 685(1), 2012, pp. 121-134.

[72] A.Peterson, J. Soberón, R. Pearson, R.Anderson, E. Martínez-Meyer, M.Nakamura, M.Araújo, M. "Ecological Niches and Geographic Distributions," Princeton University Press, 2011.

[73] S.A. Afanasyev, Y.A. Gupalo, O.V. Manturova, "Distribution and peculiarities of biology of the pumpkinseed *Lepomis gibbosus* (*Perciformes: Centrarchidae*) in the water bodies of Kiev City," Hydrobiological Journal 53, 2017, pp. 14-25.

[74] T. Nakazato, D.L. Warren, L.C. Moyle, "Ecological and geographic modes of species divergence in wild tomatoes" American Journal of Botany 97, 2010, pp. 680-693.

[75] V.Tytar, O. Nekrasova, M.Pupins, A. Skute, L. Fedorenko, A. Čeirāns, "Modelling the range expansion of pumpkinseed *Lepomis gibbosus* across Europe, with a special focus on Ukraine and Latvia," North-Western Journal of Zoology, 18 (2), 2020, pp. 143-150.