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Prospects for the Spread of the Invasive Oriental River Prawn *Macrobrachium nipponense*: Potentials and Risks for Aquaculture in Europe

Oksana Nekrasova [1,2,3,*], Anastasiia Lepekha [4], Mihails Pupins [3], Arturs Škute [3], Andris Čeirāns [3], Kathrin Theissinger [5,6], Jean-Yves Georges [2] and Yuriy Kvach [4]

1 I. I. Schmalhausen Institute of Zoology, National Academy of Sciences of Ukraine, 01030 Kyiv, Ukraine
2 Université de Strasbourg, CNRS, IPHC UMR7178, F-67000 Strasbourg, France; jean-yves.georges@iphc.cnrs.fr
3 Institute of Life Sciences and Technologies, Daugavpils University, LV-5400 Daugavpils, Latvia; mihails.pupins@gmail.com (M.P.); arturs.skute@du.lv (A.Š.); cuskisa@gmail.com (A.Č.)
4 Institute of Marine Biology of the NAS of Ukraine, 65048 Odesa, Ukraine; makiiash1@gmail.com (A.L.); yuriy.kvach@gmail.com (Y.K.)
5 Institute for Insect Biotechnology, Justus Liebig University Giessen, Heinrich-Buff-Ring 35, 35392 Giessen, Germany; kathrin.theissinger@agrar.uni-giessen.de
6 Fraunhofer Institute for Molecular Biology and Applied Ecology, Ohlebergsweg 12, 35392 Giessen, Germany
* Correspondence: oneks22@gmail.com; Tel.: +38-067-217-1970

Abstract: Climate change has amplified the threat posed by aquatic invasive species as potential disruptors of biodiversity and ecosystem functioning. Species Distribution Models (MaxEnt) based on original data and ecological variables have identified contemporary seven global centers of the oriental rivel prawn *Macrobrachium nipponense* distribution: the native range in East Asia, Northern, Western and Eastern Europe, the Irano-Turanian region, and North and South America. By 2050, further expansion in Europe is expected, likely due to climate change, particularly temperature changes (Bio1) and rain precipitation during the warmest quarter (Bio18). However, the species may see a range reduction in southern Europe due to lower precipitation and increased droughts related to climate change. Therefore, a northward shift in the range of the species is also predicted. In the context of global change, and especially biological invasions, this study highlights the risks of introducing aquaculture based on *M. nipponense* and recommends controlling such economic activities, which are associated with a high risk for native species and ecosystems. Further, long-term monitoring is needed to assess impacts and to efficiently manage *M. nipponense* populations that are already present in their non-native habitats, for mitigating their negative effects on native species and ecosystems worldwide.

Keywords: aquaculture; biological invasion; climate change; thresholds; species distribution modelling

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1. Introduction

In the modern world, where the need for sustainable and efficient food production methods are constantly growing, integrated mariculture and aquaculture are becoming key areas of innovation in the fisheries sector [1]. These sectors offer solutions for ensuring food security, sustainable use of water resources, and enhancing the biodiversity of natural ecosystems. According to the Food and Agriculture Organization of the United Nations (FAO), global aquaculture production exceeds 6 million tons per year, with Asia contributing the most, highlighting the significance of this industry at an international level [2,3].

However, despite the obvious benefits, aquaculture carries significant risks associated with invasive species. The introduction of non-native fish species through aquaculture can alter the original fish biogeography, leading to the loss of community uniqueness and faunal homogenization. In some countries, the main species used in aquaculture pose high risks to local fish diversity and conservation [4]. These impacts add to the more direct effects of aquaculture, such as increased input of nutrients and organic matter, changes in habitat and water quality, spread of diseases, and loss of native population viability due to hybridization, among others. It is recommended that local management focuses on reducing these risks by using more appropriate species, based on risk assessment and precautionary principles [5,6].

In many cases, biological invasions result from intentional introductions, mainly related to commercially important species such as for aquaculture [7,8]. Invasive species have become a major problem for ecosystems worldwide due to their potential impacts on native biodiversity and ecosystem functioning [9–11]. The oriental river prawn *Macrobrachium nipponense* (De Haan, 1849) is a widely distributed Indo-Pacific species that inhabits estuaries and freshwater environments [12–15]. In Far Oriental countries, *M. nipponense* is an important commercial fisheries species, also used in aquaculture [16,17]. Between 2010 and 2018, aquaculture supplied 191–245 thousand tons of *M. nipponense* annually [18,19]. Aquaculture of prawn species such as *Macrobrachium*, including the oriental river prawn, is becoming increasingly popular due to their high adaptability and economic value [1–3].

The oriental river prawn has been introduced into natural habitats and cooling reservoirs of thermal power stations, with reports of invasions in the White Oak River Basin (NC, USA) since 2014 [20]. In the 1960s, this species was introduced to the former Soviet regions of the Yangtze River. It subsequently spread to Uzbekistan, Kazakhstan, and the cooling reservoirs of power plants in Russia. In Europe, intentional introductions have been documented since the 1980s in Belarus, Moldova, and Ukraine, where the species was deliberately introduced into cooling reservoirs of power plants [21,22]. Numerous introductions have also been recorded in Asian countries, particularly in the Far East, including Laos, Thailand, Malaysia, Singapore, and the Philippines [23–26]. In the Middle East, the species inhabits brackish marshes and lagoons in southern Iran and Iraq [27–30]. Additionally, introduced populations have been registered in Central Asia and the Caucasus [31,32] (see also references in [33]).

Until the 2000s, the oriental river prawn was not recorded in the Dniester basin (Ukraine), but its populations later appeared in the Cuciurgan Reservoir and the Dniester delta [33]. Between 2013 and 2016, the oriental river prawn expanded its range, being found in various areas of the Dniester estuary and in fish farming ponds. Since 2017, it has also been observed in water bodies near the town of Sarata in the Odesa region, indicating further range expansion. Recently, the range of the oriental river prawn has expanded in Europe, including southwestern Ukraine, southern Moldova, eastern Romania, and Bulgaria [33–37]. Thus, this invasive species now covers the basins of the Dniester and Danube rivers, as well as small lagoons and estuaries in southwestern Ukraine.

In its native range, the species primarily inhabits deltaic and estuarine zones of rivers, showing tolerance to both fresh and brackish waters (6–12‰) [38–41]. It typically reaches a length of 5 to 8 cm and prefers clean, lentic (fast-moving) waters with a pH of 6.5 to 7.5 and a temperature range of 20 to 28 °C. In Ukraine, the oriental river prawn has been found in salinities up to 6‰, but it can successfully survive in salinities up to 10‰ [40]. The spawning season occurs in July-August in temperate regions, but continues year-round in tropical areas [39,42].

In recent years, the oriental river prawn has established two independent invasion centers in the Ponto-Caspian basin [33,43,44]. It has also recently established itself in southern Ukraine, raising questions about its environmental impacts and resource potential, given its remarkable adaptability to the temperate conditions of Eastern Europe. Therefore, the goal of this work is to study the potential spread of the oriental river prawn in Europe both at present and in the future, by investigating three key areas:

1. Identifying the oriental river prawn global distribution centers.
2. Analyzing the potential of oriental river prawn spread in Europe.
3. Assessing aquaculture potential and risks in river ecosystems of Eastern Europe.

2. Materials and Methods

2.1. Occurrence Data Collection

For collected data we conducted during field sessions from 2020 to 2024 in the Black Sea region, in the basins of major rivers such as the Danube and Dniester, and in locations like the Sukhyi Lyman and Khadzhibey estuaries. In total, 10 localities with the oriental river prawn were found (original data not published; Figure 1). We also analyzed 22 published papers (including 7 references to grey literature) representing prawn findings in 10 countries of Europe and Western/Central Asia, such as Belarus, Bulgaria, Iran, Iraq, Kazakhstan, Moldova, Romania, Russia, Ukraine, and Uzbekistan. Additionally, the prawn's range in North America was reviewed using the U.S. Geological Survey's Nonindigenous Aquatic Species Database [20]. Based on original and literary data, as well as an analysis of open data from GBIF [45], we created a filtered database of oriental river prawn findings (all records are non-duplicate).

Figure 1. Collection of material (*M. nipponense*) for research in Odesa region, Ukraine. (**A**)—1 × 0.5 m dipnet, 6-mm mesh, used for sampling; (**B**)—sampling in a canal in Vylkove, Danube delta.

To account for sampling bias, we used the nearest neighbour distance ('ntbox' package in R; [46]) method for thinning the data. Occurrence points that were ≤0.1 units away from each other were removed to avoid errors due to spatial autocorrelation. As a result, the number of points significantly decreased to 532 of *M. nipponense*.

2.2. Environmental Data

For building the Species Distribution Models (SDMs) we used 14 bioclimatic variables from the CliMond dataset ([47]; https://www.climond.org/ (accessed on 28 November 2022), A1B) and used separately 12 WorldClim bioclimatic factors ([48]; MIROC-6 ssp126, https://www.worldclim.org/ (accessed on 21 November 2022)) (Table 1). The bioclimatic variables were utilized for the time periods: current (1970–2000) and 2050 (2041–2060), with a resolution of 2.5 arc-minutes (~5 km) for GIS modeling.

Table 1. Bioclimatic variables from the CliMond dataset (14—[1]), WorldClim dataset (12—[2]).

Number	Variable
Bio01 [1,2]	Annual mean temperature (°C)
Bio02 [1]	Mean diurnal temperature range (mean(period max-min)) (°C)
Bio03 [1,2]	Isothermality (Bio02 ÷ Bio07)
Bio04 [2]	Temperature seasonality (Coefficient of Variation)
Bio05	Max temperature of warmest week (°C)
Bio06 [1]	Min temperature of coldest week (°C)
Bio07	Temperature annual range (Bio05-Bio06) (°C)
Bio08	Mean temperature of wettest quarter (°C)
Bio09	Mean temperature of driest quarter (°C)
Bio10 [1,2]	Mean temperature of warmest quarter (°C)
Bio11 [1,2]	Mean temperature of coldest quarter (°C)
Bio12 [1,2]	Annual precipitation (mm)
Bio13	Precipitation of wettest week (mm)
Bio14 [1]	Precipitation of driest week (mm)
Bio15 [1,2]	Precipitation seasonality (Coefficient of Variation)
Bio16	Precipitation of wettest quarter (mm)
Bio17 [2]	Precipitation of driest quarter (mm)
Bio18 [1]	Precipitation of warmest quarter (mm)
Bio19	Precipitation of coldest quarter (mm)
Bio25 [1]	Radiation of driest quarter (W m^{-2})
Bio28 [1]	Annual mean moisture index
Bio31 [1]	Moisture index seasonality (Coefficient of Variation)
Bio34 [1]	Mean moisture index of warmest quarter
Tmin1 [2]	Minimum temperature in January
Pr6 [2]	Precipitation in June
Pr4 [2]	Precipitation in April
Elev [2]	Elevation (Relief)

2.3. Model Building

Modeling ecological niches and species distribution is an important tool in ecology and natural resource management. It allows predictions on how species may respond to environmental changes, including climate change, and aids in developing strategies for biodiversity conservation and invasive species management. In the case of oriental river prawns, modeling is necessary to understand their potential spread and impact on ecosystems where they may be introduced. This is particularly important in the context of globalization and climate change, where species can quickly move and adapt to new conditions.

In our study, we applied Species Distribution Modeling (SDM) methods to predict the geographic distribution of oriental river prawns based on a created database, which also includes original research. SDM is a powerful tool that allows for the assessment of potential species habitats, taking into account various ecological factors such as climatic conditions (CliMond and WorldClim datasets), terrain, and the availability of water resources [49,50]. These data were chosen for their relevance in the context of a changing climate, allowing for more accurate modeling of potential species habitats under current conditions and predicting trends in prawn distribution in the future.

Climatic factors play a key role in determining habitat boundaries as they influence the viability and spread of species. Our modeling encompassed the entire distribution area, utilizing dispersal points from both the native range and documented introductions on other continents. This approach allowed us to encompass the full potential ecological niche of the oriental river prawns and identify regions that may support its establishment and spread. We used the MaxEnt algorithm [46], running 35 replicates, applying a machine learning technique known as maximum entropy modeling. This approach requires only presence data, making it particularly relevant for managing invasive species. To evaluate the performance of the SDM, we used ROC (Receiver Operating Characteristic) metrics [49–51] and a confusion matrix. The performance of the MaxEnt model is typically assessed using the ROC method, where the area under the ROC curve (AUC—Area Under the Curve) serves as a measure of prediction success. The ROC curve graphically represents the relationship between the false positive rate and sensitivity across different thresholds. Classification guidelines adhere to the traditional academic grading system: very good (0.8–0.9) and excellent (0.9–1.0). Models were evaluated using the True Skill Statistic (TSS) [52,53]. Niche clustering was performed using the 'ntbox' package in R, which provides methods for k-means clustering and allows the projection of results in geographic and environmental spaces (known as Hutchinson's duality) [46,54], sometimes referred to as an ecological envelope. Visualization of the model with colors shows the calculated probability of suitable conditions: red indicates a high probability of suitable conditions for the species; green indicates conditions similar to those where the species is found; shades of blue indicate unlikely conditions. Visualization and analysis of the model were conducted using programs such as SagaGis and QGIS.

3. Results

3.1. Oriental River Prawn Global Distribution Centers

As a result of research and the creation of models using CliMond variables, seven contemporary centers of distribution for *M. nipponense* were identified worldwide (Figure 2): (1) Native range—Oriental region, which is the original habitat of the species. (2) Northern European region, which includes the countries of the Baltic basin where *M. nipponense* can be used in aquaculture. (3) Western European region. (4) Eastern European region. (5) The Irano-Turanian region, representing a vast area that covers parts of Western and Central Asia. (6) North America, where the presence of this species was also reported. (7) South America, which has become a new range for *M. nipponense*.

According to our models, by the year 2050, further expansion of the range of *M. nipponense* in Europe and North America is expected, as a result of climate change and other factors. The potential spread of this species in Northern Europe, particularly in the Baltic region countries (Figure 2, №2), is also noteworthy. Furthermore, the model demonstrates excellent performance, with an average training AUC (Area Under the Curve) of 0.984 and a standard deviation of 0.001 across the replicate runs.

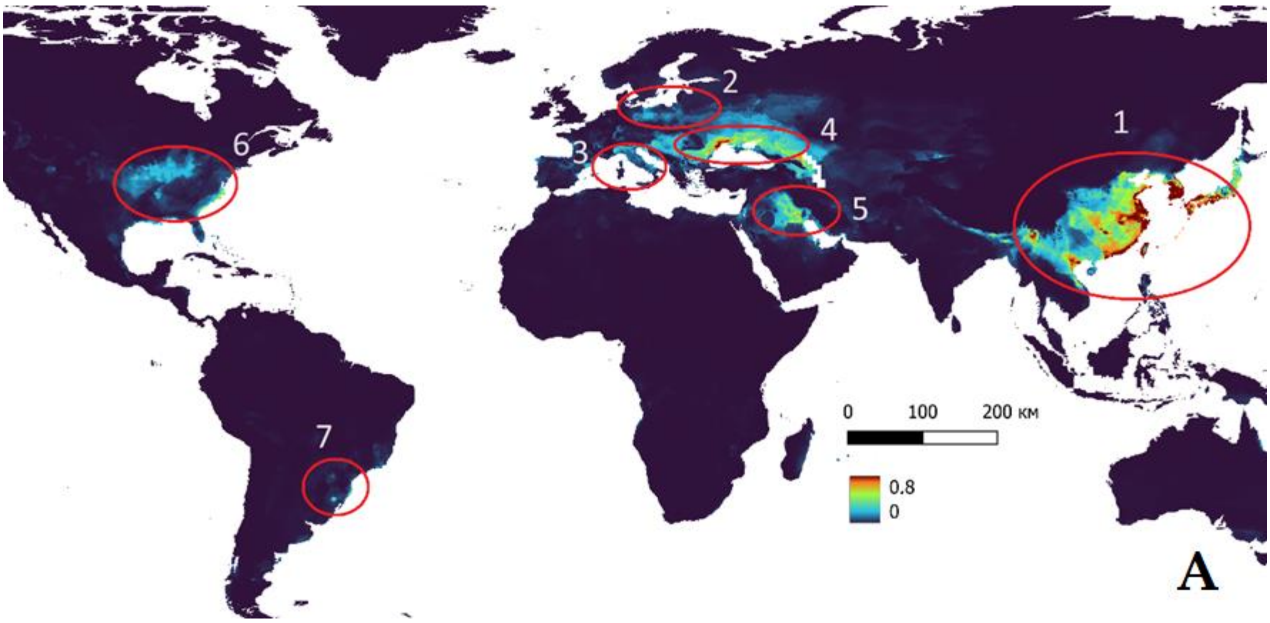

Figure 2. *Cont.*

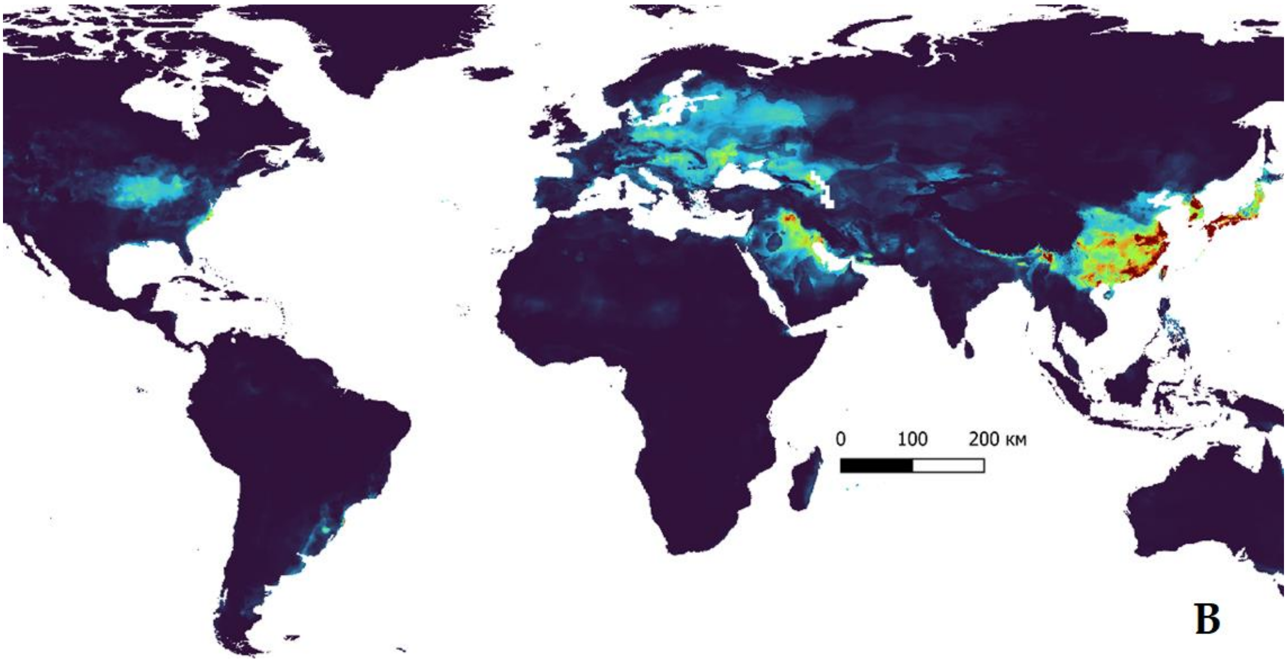

Figure 2. Results of the analysis of SDM Maxent of *M. nipponense*: (**A**) current; (**B**) 2050 (2041–2060) (green-yellow color > 0.5, CliMond dataset; №1–7 see the explanation in the text).

In the context of studying the impact of climatic conditions on the distribution of *M. nipponense*, the variable Bio18, which reflects the amount of precipitation during the warmest quarter of the year, emerges as the most significant factor. It accounts for 18.2% of the influence, highlighting its importance in predictive models for the species' distribution. This suggests that changes in precipitation levels during the warmer months can have a substantial direct positive impact on populations of *M. nipponense*. Also of great importance is the variable—Bio3 Isothermality (taking into account Temperature annual range between Max temperature of warmest week and Min temperature of coldest week)—12.9%.

3.2. Oriental River Prawn Spread in Europe

During our research conducted in the Black Sea region and the basins of major rivers such as the Danube and Dniester, as well as the Sukhyi Lyman and Khadzhibey estuaries from 2020 to 2024, we identified ten significant discovery sites of *M. nipponense* (Figures 1 and 3; Table 2). Moreover, this species was found in both large water bodies and rivers, as well as in small enclosed water bodies such as in Paliivka. Therefore, it was important to assess which factors influence the distribution of this species in Europe.

Based on the modeling results, it is evident that under current conditions, the greatest distribution is observed in the southern part of Ukraine, particularly in the Black Sea region, the Odesa-Kherson area, and the Sea of Azov region (see Figures 3 and 4). The model for *M. nipponense*, developed using WorldClim variables, similarly indicates a northward range shift in Europe.

As far as European populations are concerned, the major factors of occurrence of the thermophilic *M. nipponense* are Bio01 Annual mean temperature—29.0% and Bio3 Isothermality—28.3%. Isothermality reflects the stability of temperature conditions throughout the year. Also important for modeling the distribution of *M. nipponense*—Bio14 (Precipitation of driest week).

Figure 3. Habitats and research objects *M. nipponense* in the Black Sea region, Ukraine. (**A**)—typical habitat of the prawn in the Dniester delta; (**B**)—sampled individuals; (**C**)—fishermen catch; (**D**)—commercial-size catch of the prawn, together with local crustaceans.

Table 2. Occurrence data of the Oriental river prawns *M. nipponense* in the Black Sea, Ukraine (field records, 2020–2024).

Drainage	Body of Water	Locality	Geographic Coordinates
Danube basin	Danube delta	Canals in the City of Vylkove	45.410778 °N, 29.606139 °E
	Lake Kuhurlui	Novosilske village	45.301917 °N, 28.594889 °E
	Lake Kytay	Chervonyi Yar village	45.582472 °N, 29.193389 °E
Dniester basin	Cuciurgan Reservoir	Lymanske	46.655028 °N, 29.959972 °E
	Turunchuk River	Canals in Yasky village	46.519667 °N, 30.100639 °E
	Lake Safiany	City of Biliiaivka	46.471750 °N, 30.195639 °E
	Lower Dniester	Maiaky village	46.407735 °N, 30.264684 °E
	Dniester Estuary, Karagol Bay	Maiaky village	46.406306 °N, 30.265306 °E
Other drainages	Sukhyi Lyman	Dalnyk River mouth	46.395426 °N, 30.623330 °E
	Khadzhibey Estuary	Paliivka village	46.644139 °N, 30.461472 °E

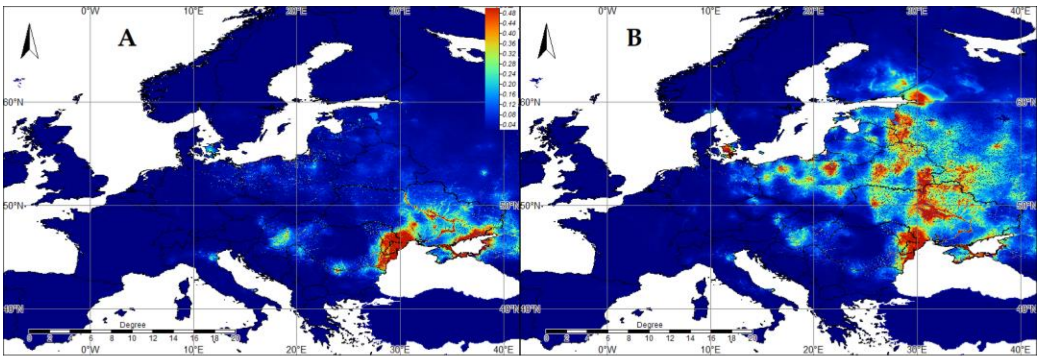

Figure 4. Potential (probabilistic) model SDM of *M. nipponense* expansion built in the Maxent program in Europe based on WorldClim dataset: (**A**)—current; (**B**)—2050 (2041–2060) (red color > 0.5).

4. Discussion

This study identified the main ecological factors influencing the current distribution of potentially suitable habitats for the oriental river prawn *M. nipponense* and allowed for the analysis of the potential medium term spread of this exotic species by 2050 in the context of climate change. Consistently, as a result of clustering the niches of global distribution centers for the oriental river prawn, three distinct niche types were identified (Figures 2 and 5) in Eurasia: the native Asian (Figure 2: №1), the European (№2–4), the Irano-Turanian (№5), and utilizing the prescribed methodology, a geographic map is presented, delineating the distribution of data points within each ellipsoid, with color coding employed to facilitate the association of each data point to its respective cluster. Accompanying the 3-dimensional visualization of these clusters is a detailed geographic map (Figure 5A). This map clearly outlines the distribution of data points within each ellipsoid, employing a color-coding system to streamline the identification of each data point with its corresponding ecological niche. Leveraging this sophisticated tool, which is based on the theoretical frameworks of Colwell and Rangel (2009) [46,54] and Hutchison's duality, provides a vivid depiction of the ecological niches and their geographical distribution [55]. Furthermore, as shown in Figure 5B, the European niche of this species is currently small and intersects with all the marked niches. This adaptability is particularly relevant in the context of climate change, indicating that the species may have significant potential for future expansion as temperatures continue to rise. The analysis reveals that, despite the considerable environmental differences between the native Asian and European habitats, the species has successfully adapted to the forecasted conditions.

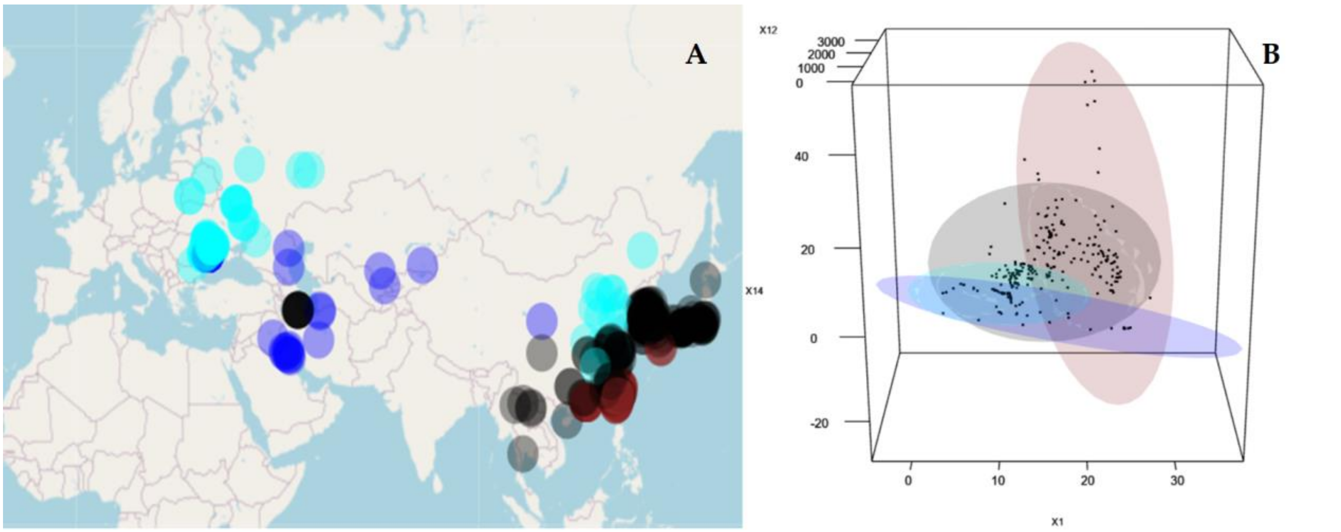

Figure 5. Niche clustering (geographic space, ecological preferences of species, current CliMond, [46]) for *M. nipponense*: (**A**)—map with the 4 number of clusters, (**B**)—the 3-dimensional plot with ellipsoids representing the 4 number of clusters (black—native range and similar (Figure 2 center 1), light blue—European and similar (Figure 2 centers 2–4), blue (Figure 2 center 5); see the explanation in the text).

On a global scale, the main limiting factor for the distribution of the oriental river prawn is the availability of water during the warmest period (Bio18). Given that precipitation in the warm season can directly affect the availability of aquatic resources necessary for the life cycle of *M. nipponense*, this factor could dictate the possibilities for the expansion or contraction of its range. For instance, an increase in precipitation levels may lead to a rise in population numbers due to the expansion of available and suitable habitats, as well as improving conditions for breeding this species in aquaculture. Conversely, a decrease in precipitation could lead to the opposite effect, causing a reduction in available habitats and worsening conditions for reproduction and survival of *M. nipponense*. This could result in a reduction in range and population numbers, making variable Bio18 a critical factor to consider in conservation and management strategies for this species.

However, in Europe, the distribution of this species is primarily limited by the temperature regime, specifically the mean annual temperature (Bio01) and isothermality (Bio3), highlighting the importance of stable temperature conditions, which can significantly impact its survival. High isothermality, reflecting smaller temperature fluctuations between seasons, creates more stable conditions for the habitat of *M. nipponense*, promoting better survival and reproduction. Stable temperature conditions can enhance the survival and reproduction of *M. nipponense*, as extreme temperature fluctuations can negatively affect their physiology and resource availability, including water. This is indicated by the factor (Bio14 Precipitation of the Dry week), which can be critically important for the survival and reproduction of this invasive species. Additionally, when adding the terrain variable to the modeling, this variable will have a determining significance, contributing up to 42.3% to the model.

It is predicted that as a result of climate change in the future (by 2050), the greatest dynamics in the range of this species can be observed in Eastern Europe, especially in connection with the expected expansion of its range by 1.6 times to the north of the continent. Similar prospects are observed for many other thermophilic species, the distribution of which is particularly influenced by factors related to humidity [56]. Our data indicate that the Baltic countries may become a new promising region for the spread of *M. nipponense.* Our modeling confirms that the presence of stable and large watercourses, such as the Dnieper River, plays a key role in the conservation and spread of this species, where a suitable humid microclimate will be observed. The significance of the Dnieper eco-corridor in the spread of many thermophilic species was described earlier [57]. Thus, we observed an increase in the occurrence of such species as *Lepomis gibbosus* in the Middle Dnieper region [58]. In contrast, in the southern regions of Europe, a reduction in range of the oriental river prawn is expected due to a decrease in precipitation and an intensification of drought periods. This may lead to the drying up of small water bodies, which, in turn, will negatively affect the populations of *M. nipponense*. Nevertheless, it is necessary to take into account the negative experience of hydrobiont kills in large rivers, which may be associated with climate change and anthropogenic factors [59,60]. This underscores the need for more detailed study of the impact of climatic and ecological changes on the viability of *M. nipponense* in different types of water bodies.

In the context of aquaculture in the Baltic countries, it is advisable to conduct comprehensive research to assess the possible impact of *M. nipponense* on local ecosystems and establish its potential for competition with local species. It is also important to take into account the adaptive abilities of this invasive species to extreme conditions at the edge of its distribution range. The results of our research emphasize the need to develop management strategies for *M. nipponense* that consider both its potential for spreading and its possible negative impacts on local species and ecosystems. Climate change and anthropogenic influences act synergistically, exacerbating the biodiversity crisis known as the sixth mass extinction. These factors create conditions in which invasive species can more rapidly colonize new territories, displacing native species [61,62]. This requires a comprehensive approach to addressing the issue, simultaneously considering climate change, habitat degradation, and biological invasions. The experience of introducing alien species in Europe shows that *M. nipponense* aquaculture should be controlled. In places where the oriental river prawn is already used, it is recommended to monitor its use, and where it has not established itself, it is advisable to conduct further research or even banned it due to the risk of invasion. The introduction of alien species can have devastating consequences for local ecosystems. As a most reknown and stricking example, is the introduction of alien crayfish for aquaculture in Europe that has led to repeated crayfish plague outbreaks and significant losses among all native species [63]. This serves as a reminder that economic benefits should not outweigh ecological risks. The protection of local ecosystems must be a priority, and any decisions regarding the introduction of new species should be controlled, as shown here from our data.

5. Conclusions

As a result of the research and modeling carried out, we have identified seven main global centers for the potential spread of *M. nipponense*. The territory of Eastern Europe has been highlighted as particularly suitable for the spread of this invasive species. In the context of climate change, by the year 2050, the Baltic countries could be considered the most promising for the expansion of the *M. nipponense* range, which is expected to increase by 1.6 times. This highlights the potential risks associated with the introduction of such invasive species into the ecosystems of Northern Europe, as it may be for aquaculture due to its high economical values reported in its native place, Asia. All these conclusions must also be taken into account when developing management plans and to undertake long-term monitoring of the impacts and potential widespread establishment of this species. This will help mitigate any negative effects on native ecosystems and ensure that the introduction of *M. nipponense* is regulation and also banned into new areas. The spread of *M. nipponense* in Europe, and especially in Ukrainian water bodies, requires ongoing monitoring and research to assess its ecological impact, ensure sustainable population management and mitigate potential negative impacts on local biodiversity and ecosystem functioning. The historical role of similar aquacultures in Southern Ukraine as a gateway for the entry of invasive alien species into Europe and their subsequent spread through the Southern European Invasion Corridor underscores the urgency of addressing the presence of invasive species in this region and preventing any introduction in the future.

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Data Availability Statement: Data derived from public domain resources:1. Species presence records oriental river prawn *Macrobrachium nipponense* (De Haan, 1849): GBIF.org (22 May 2024) GBIF Occurrence Download https://doi.org/10.15468/dl.bf6zjp. 2. Environmental data: The WorldClim v.2 website (http://www.worldclim.com/version2; accessed on 21 November 2022); The CliMond v.1.2 (current, 2050) datasets were downloaded from https://www.climond.org/ resolution of 2.5 arc-minutes (~5 km) (accessed on 28 November 2022). 3. Software: Maxent, https://biodiversityinformatics.amnh.org/open_source/maxent/; The R package "ntbox", https://github.com/ropensci/; The Saga GIS software, https://saga-gis.sourceforge.io/en/index.html (accessed on 30 November 2022).

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