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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

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Abstract: The potential distribution of tropical fish species in Eastern Europe—*Gambusia holbrooki* (introduced for biological control) and *Poecilia reticulata* (aquarium species, found in waste waters of big cities)—tend to be of particular interest in terms of global climate change. After GIS modeling of our own data and findings listed in the GBIF databases (2278 points for *G. holbrooki* and 1410 points for *P. reticulata*) using the Maxent package and 'ntbox' package in R, 18 uncorrelated variables of 35 Bioclim climatic parameters from CliMond dataset, it was found out that by 2090 guppies will appear in the south of Ukraine (Danube river's estuary, as well as in several places in the Caucasus and Turkey with habitat suitability > 0.3–0.5). *G. holbrooki* will also slightly expand its range in Europe. Limiting factors for *G. holbrooki* distribution are: bio1 (Annual mean temperature, optimum +12–+24 °C) and bio19 (Precipitation of coldest quarter (mm). Limiting factors for *P. reticulata* are: bio1 (optimum +14–+28 °C), bio4 (Temperature seasonality), bio3 (Isothermality). Unlike *G. holbrooki*, guppies prefer warmer waters. Such thermophilic fish species do not compete with the native ichthyofauna, but they can occupy niches in anthropogenically transformed habitats, playing an important role as agents of biological control.

Keywords: ecological niche model; distribution; aquaculture; mosquitofish; climate change; expansion

1. Introduction

Considering the prospects associated with the appearance of invasive species of animals at a new continent, some of the possible consequences are usually missed. It is often expected that the distribution and naturalization of invasive alien species can be controlled. However, this cannot always be possible since in open biosystems (natural and anthropogenic), in addition to other human activities leading to the spread of invasive alien species, the influence of changing climatic conditions, as the most global consequence of human activity takes place. However, the influence of all these negative factors (moving species between countries, uncontrolled release, wrong usage as agents of bimethod, accidental introduction, hunting, disbalancing of local ecosystems, etc.) as a whole can lead to the suppression of native animal species [1] and the emergence of species new to the local environment [2–7]. These factors can actively displace not only representatives of the ichthyofauna, but also batrachofauna [8]. Therefore, the main questions that we must ask ourselves are as follows: (1) What is the preferable (optimal) environment for an invasive species and in which regions naturalization and appearance of the species is possible; (2) what consequences of this appearance could be for native species and for the environment in general; (3) where do invasive species come from and what are the possible ways to avoid this; 4) what can influence invasive species as a limiting factor (besides climate conditions)—predators, parasites, illnesses. Of great interest is the appearance (or prospects of appearance) in temperate latitudes of thermophilic poikilothermic animals with their own strategy of viviparity, which gives them an opportunity to reproduce even in non-optimal conditions (for example, in human transformed territories). They also thrive and reproduce in both fresh and brackish water. Representatives of the genera *Gambusia* [9] and *Poecilia* [10] came to Europe as agents of a biological method for controlling the malaria mosquitos at the beginning of 20th century (they were released into the reservoirs of Western Europe). In addition, previously they also were bred in quantities in aquarium farms as aquarium fish. Two closely related species of this genus were introduced in Europe for the above mentioned purpose: *Gambusia affinis* (Baird and Girard, 1853) and *Gambusia holbrooki* (Girard, 1859), but the latter species is the most widespread and occurs in Ukraine.

G. holbrooki is a viviparous freshwater fish species (Poeciliidae family) originating from southern areas of North America. The species demonstrates great plasticity in the preference of comfortable water temperatures, thriving at +31–+38 °C, but being able to survive beyond these values [10]. This planktivorous species was used as an agent of biological control and was introduced in 1921 to the Iberian Peninsula for the first time to combat malaria. Later on the fish expanded an area of its invasion to Italy in 1922 and other Mediterranean countries, like Greece, Croatia, Spain etc. [11]. Currently this invasive alien species is well known in about 50 countries worldwide [9,12]. Besides being used to control mosquito populations, this species is known to have negative effects on local populations of aboriginal amphibian and fish species [13,14], which necessitates the study of its potential distribution, in terms of global climate change of particular importance in order to preserve local biodiversity.

P. reticulata is another viviparous freshwater fish species from North America that became invasive in Europe over recent decades. The wild form of the guppy was introduced to Europe in the 19th century. It was also used to fight malaria; thus it was introduced to many places. Being a popular polymorphic aquarium species, and due to their better resistance to colder water (up to +12 °C), guppies became invasive as a result of many accidental releases from aquaria [10,15]. Their ability to store sperm for months made it possible even for a one single gravid female to start a new population [16]. A wild population of guppies permanently lives in the Moskva river in the area of warm water discharge in Lyubertsy (Kuryanovsk drains) and in other places of this river [17,18]. Recently, in the Upper Volga basin, numerous self-reproducing populations of guppies have been noted in the regions of large cities (Tver, Yaroslavl, Rybinsk) in the areas of heated water discharge, as well as in settling ponds in facilities for the purification of domestic wastewater [19,20]. In their homeland, the island guppy populations live in brackish and seawater; they are bright in color and large in size. Optimal conditions for guppies include: clean water with a temperature of about +24 °C (the range being +16–+30 °C), the presence of zones with vegetation and free for swimming, a varied diet with a substantial proportion of live food. There are no data on the biology of this species from the Moskva river. It is known that there it reaches a high number and can be caught with a net in large quantities. For water bodies of the Upper Volga, there is an indication that it does not occur in water bodies with a temperature under +17 °C [20].

Such assumptions about appearance and distribution of these species in Eastern Europe are most relevant in connection with their potential usage as agents of biological control against the emergence of new carriers of various diseases—blood-sucking insects [21]. Therefore, the purpose of our work was to study both climatic indicators of environmental optima for these invasive alien species, and possible spread of these species over Eastern Europe in space and time.

2. Materials and Methods

2.1. Occurrence Data Collection

Occurrence data were collected from the original datasets [22], collection materials (I. I. Schmalhausen Institute of Zoology, National Academy of Sciences of Ukraine, Kyiv), GBIF databases [23,24]—all non-duplicate. We also studied the typical biotopes generally occupied by these fish species in Eastern Europe (Ukraine and Turkey) within 2012–2021 period of conducted field research (20 expeditions) (Figure 1). Fish were registered visually or caught by a manual fishing net (d = 2 mm) with subsequent species determination and release at the place of capture; the biotopes were photographed. To account for sampling bias, we used the nearest neighbor distance ('ntbox' package in R [25]) method to thin the data, where occurrence points that were $\leq$0.1 units away from each other were removed to avoid errors due to spatial autocorrelation. As a result, the number of points has significantly decreased; from 26,140 total points to 2278 for *G. holbrooki* and from 4200 points to 1410—for *P. reticulata.*

Figure 1. Biotope occupied by (**A**)—*P. reticulata* along the Bortnychi sewage drain (Ukraine, localities are marked with red circles); (**B**)—*G. holbrooki* is found in roadside fresh water bodies (Turkey).

2.2. Environmental Data

We used bioclimatic variables from the CliMond dataset (https://www.climond.org/ (accessed on 27 December 2020), following A1B climate change prediction scenario, of MIROC H global climate model. The above mentioned variables represent annual trends (e.g., mean annual temperature, annual precipitation) and extreme limiting environmental factors (e.g., temperature of the warmest month, precipitation in the wettest quarter), that are predicted for the whole planet (or its particular regions) and are known to influence species distributions [26]. Of 35 bioclimatic variables, highly correlated (r > 0.7) predictors were chosen using the 'virtualspecies' package in R, resulting in a selection of 18 variables predicted for 1975 (1970–2000) and 2090 (2081–2100) years. The following bioclimatic variables (CliMond) were chosen to be used in the analysis: 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), bio14 Precipitation of driest week (mm), 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), bio18 Precipitation of warmest quarter (mm), bio25 Radiation of driest quarter (W m^{-2}), bio28 Annual mean moisture index, bio31 Moisture index seasonality (C of V), bio34 Mean moisture index of warmest quarter.

2.3. Model Building

In order to illustrate the niche-biotope dualism (known as Hutchison's duality [27])—the fact that the two invasive fish species can occupy ecological niches in different biotopes that have different combination of bioclimatic variables and make an ecological niche modelling (ENM), we used niche clustering ('ntbox' package in R [25]), which provides the opportunity to perform k-means clustering and project the results in the geographic and environmental spaces in a form of a world's map. The map shows the world's areas where the two fish species were found in biotopes that differ from those within their home range (different combinations of variables in places of species findings are market with differently colored circles).

Species distribution modelling (creation of standard distribution models or SDMs) was used to determine the potential change of distribution ranges of invasive alien species in new environments with time (MaxEnt [28] with 35 replicates, DivaGis (version 7.5; using CliMond dataset of current and predicted variables)). The Maxent software (version 3.4.4, [28,29]) was utilized for modelling, using the default settings. Maxent, unlike other distributional modelling techniques, uses only presence (registration points) data instead of presence and absence data. The SDMs were shown as maps where the areas of the highest habitat suitability ($r > 0.3$–0.5) are colored in red and areas of the lowest ($r < 0.2$)—in blue when visualized in SagaGis (System for Automated Geoscientific Analyses, version 7.6.0). The evaluation metrics for the obtained SDMs (performance) included: Partial receiver operating characteristic (ROC) [29], binomial tests [30], and the confusion matrix [31]. The ROC area under the receiver-operator curve (AUC) was used for assessing the discriminatory capacity of the models: AUC > 0.9 is considered excellent. The true skills statistics (TSS) was used to make a post-modelling check of obtained SDMs based on the standard confusion matrix that represents matches and mismatches between real observations of species (collected data) and predicted theoretical points within areas of high habitat suitability according to the created SDMs [26]. Binomial test mentioned earlier, as one of standard ways for evaluating obtained SDMs' quality, allowed to determine whether test points (from obtained SDMs' .acs files) fall into regions of predicted presence more often than expected by chance, given the proportion of map pixels predicted present by the model and showed on the world's map) [30]. This also helped to visualize the difference in predicted world areas occupied by the two fish species. GIS-modelling was accomplished using visualization in SagaGis, DivaGis, QGIS (version 3.16.9) [26]. Statistical processing of the obtained data was carried out using Statistica for Windows v.10.

3. Results

3.1. Limiting Factors for *P. reticulata* Distribution

MaxEnt GIS modeling revealed the following limiting and important factors (percent contribution) for the distribution of guppies: bio4 (Temperature seasonality)—21.9%, bio3 (Isothermality)—10.6%. In this "ecological envelope" 68.1% of guppies are found in the temperature range of +10–+28 °C, mean—22 °C (bio1, Figure 2, [28]). The temperature of +10 °C may have appeared as a result of extrapolation to northern areas, where warm drains are located (in large cities, etc.). According to our observations of "wild" populations of guppies in warm water bodies of the Bortnychi aeration station in Kyiv (2011–2020; 50.3837° N, 30.6642° E, Ukraine), these fish are quite unpretentious in terms of water quality and are generally demanding to the water temperature. The total body length in males is 1.85–3.24 cm, and in females—2.00–5.50 cm. Guppies breed all year round and even in winter in warm sewage waters; in December 2020 (water temperature +16 °C) mainly juvenile individuals were registered (Figure 1A). And owing to the high water temperature, they reproduce all year round. Therefore, these fish are more synanthropic, and are more likely to get along in warm urban drains in Eastern Europe. Consequently, annual mean temperature (bio1) within the native range has optimum—+14–+28 °C, mean—24 °C (Figure 2, [28]), and this species is rather unpretentious to water quality (Figure 1).

3.2. Limiting Factors for *G. holbrooki* Distribution

On the contrary, mosquitofish can coexist in open water bodies outside the warm wastewaters of large cities and anthropogenic areas, in roadside water bodies (Figure 1B) in western and southern parts of Europe, as well as in Ukraine—in the Odessa region and the Crimea [32]. As a result of GIS modeling, it was revealed that the most important factors (percent contribution) limiting the distribution of *G. holbrooki* in Europe are: bio21 Highest weekly radiation (W m^{-2})—26.2%, bio19 Precipitation of coldest quarter (mm)—18.6%, bio1 annual mean temperature—14.7% has the optimum—+12–+24 °C (mean—+16.5 °C), within the native range of +15–+24 °C (mean—+19.5 °C, Figure 2, [28]). This fish is able to reproduce throughout the year as long as the water temperature is above +15 °C (April–November). An interesting observation is that at a water temperature below +10 °C *G. holbrooki* burrows into the silt and falls into a suspended anabiosis [33]. During severe winters when reservoirs are bound with ice, *G. holbrooki* perishes in great numbers. For instance, this species died en masse as a result of cold winter in Sochi in 2020 [34,35].

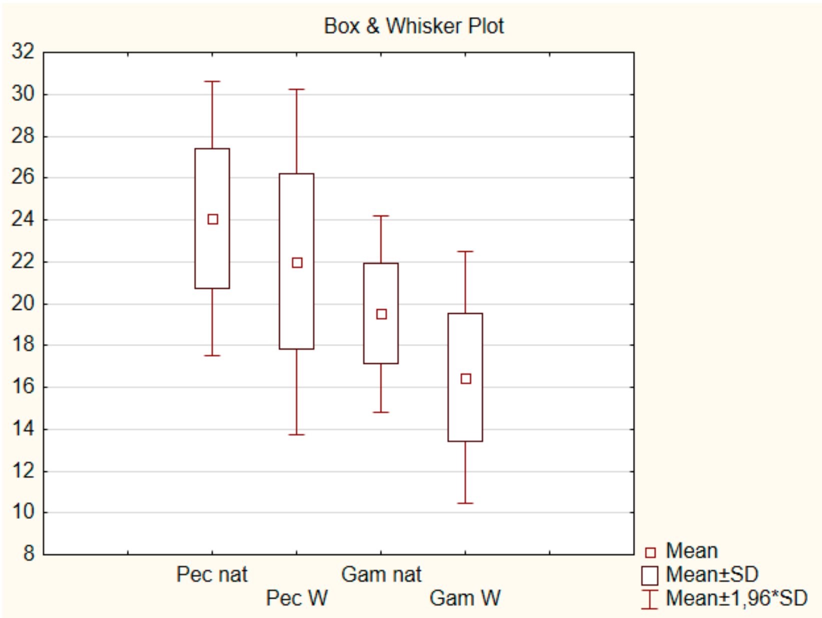

Figure 2. Plot variable bio1 Annual mean temperature (°C, CliMond, 1975 (1970–2000)) from: Pec—*P. reticulata*; Gam—*G. holbrooki*; nat—native range; W—World areas.

3.3. Niche Clustering

Using the clustering algorithms (a statistical tool which explains the difference between the variables that describe climatic conditions) for visualizing the Hutchison's duality (K-means clustering, Colwell and Rangel 2009) it was shown that the native range of American alien fish species differs in bioclimatic parameters (Figure 3). Therefore, understanding such perspectives and conditions is very important for interpreting expansion of the species range in future. Therefore, the preference for a warmer temperature regimen (Figure 2), unpretentiousness, the possibility of live birth and great popularity among fans of exotic aquacultures make it possible to "expect" more favorable conditions during climate warming. And it is even possible to adapt to new conditions.

3.4. Ecological Niche Modeling

To study the distribution of alien fish species in the present and in the future, we created two models (Maxent, CliMond 1975 and 2090) for each species (Figures 4 and 5). As a result, it was shown that taking into account tendencies of global warming till 2090, the range will increase by 1.2 times for guppies and by 1.07 times for mosquitofish. Despite the fact that these American viviparous fish species are thermophilic, they occupy different ecological niches (Figures 2 and 3), which certainly do not coincide with native northern fish species. To compare the SDM models (Maxent, CliMond 1975) of two species of American fish we used the regression module in SagaGis; the resulting coefficient of correlation was only r = 0.18, with global warming by 2090, the rate increases: r = 0.33. The similarity will become greater over time, thus suggesting that with global warming these fish species can occupy similar habitats in Eastern Europe. Nevertheless, the tendencies for the expansion of the range of these two invasive alien species in Eastern Europe (as well as in the south of Ukraine, the Caucasus) are quite realistic in the future (by 2090). Evaluating the performance of the SDM 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, we came to the conclusion that the indicators are quite high—AUC > 0.95, TSS > 0.62.

To calculate the significance of the model, we used all the American fish meeting points (see Materials and Methods, [23,24]) and the Maxent model (CliMond 2090, Figure 6 [30]). The check was done using a binomial test using the cumulative binomial probability of success of predicting correctly an occurrence given the validation data and the proportional area predicted as present in the niche model. Therefore, we can conclude that the mosquitofish has great prospects for distribution in the south of Eastern Europe, since it is less demanding on temperature factors. (Figures 2 and 6).

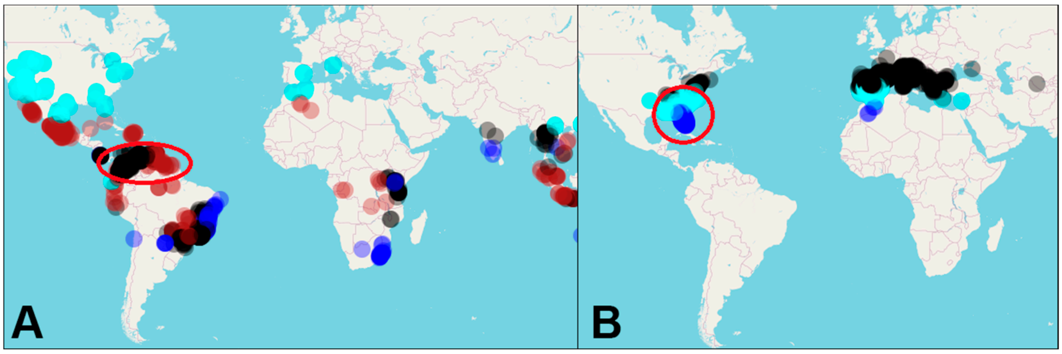

Figure 3. Niche clustering (Geographic space, CliMond 1975 (1970–2000)) from: (**A**)—*P. reticulata*; (**B**)—*G. holbrooki*, Differently coloured spots represents biotopes where the fish species was registered according to data collected from GBIF [23,24], where the species was registered and which has combination of climatic factors different from those in their native distribution area (marked with red circles).

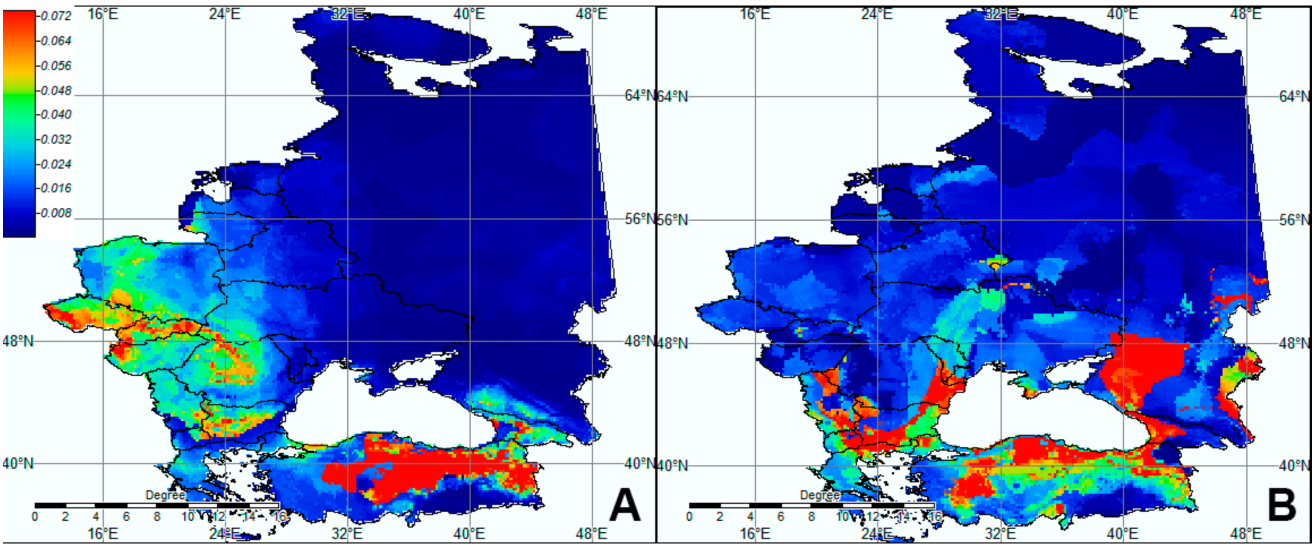

Figure 4. Potential (probabilistic) model of *P. reticulata* expansion built in the Maxent program based on the CliMond: (**A**)—1975 (1970–2000); (**B**)—2090 (2081–2100)) climatic data and GBIF data (2021). Areas of the highest habitat suitability (r > 0.3–0.5) are colored in red and areas of the lowest (r < 0.2)—in blue (SagaGis).

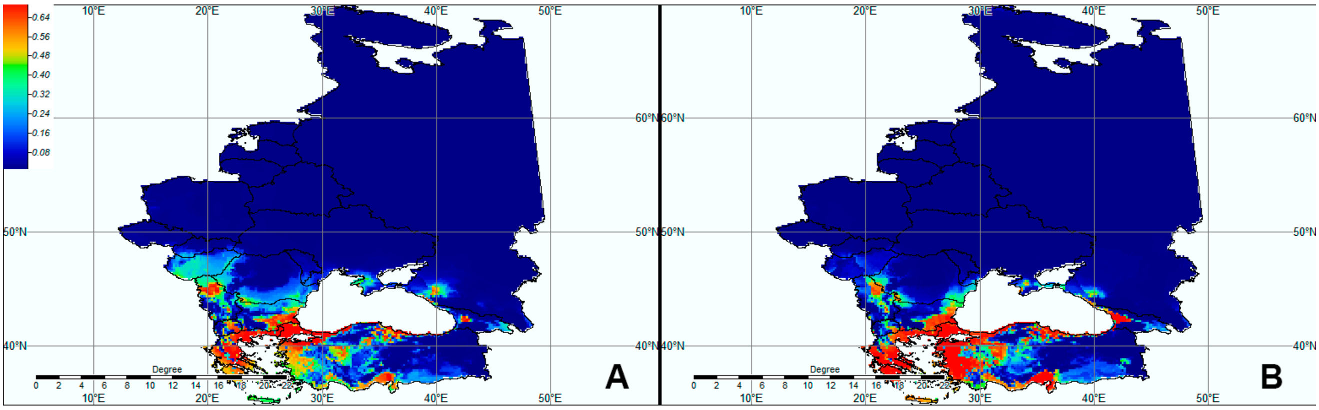

Figure 5. Potential (probabilistic) model of *G. holbrooki* world expansion built in the Maxent program based on the CliMond: (**A**)—1975 (1970–2000); (**B**)—2090 (2081–2100)) climatic data and GBIF data (2021). Areas of the highest habitat suitability (r > 0.3–0.5) are colored in red and areas of the lowest (r < 0.2)—in blue (SagaGis).

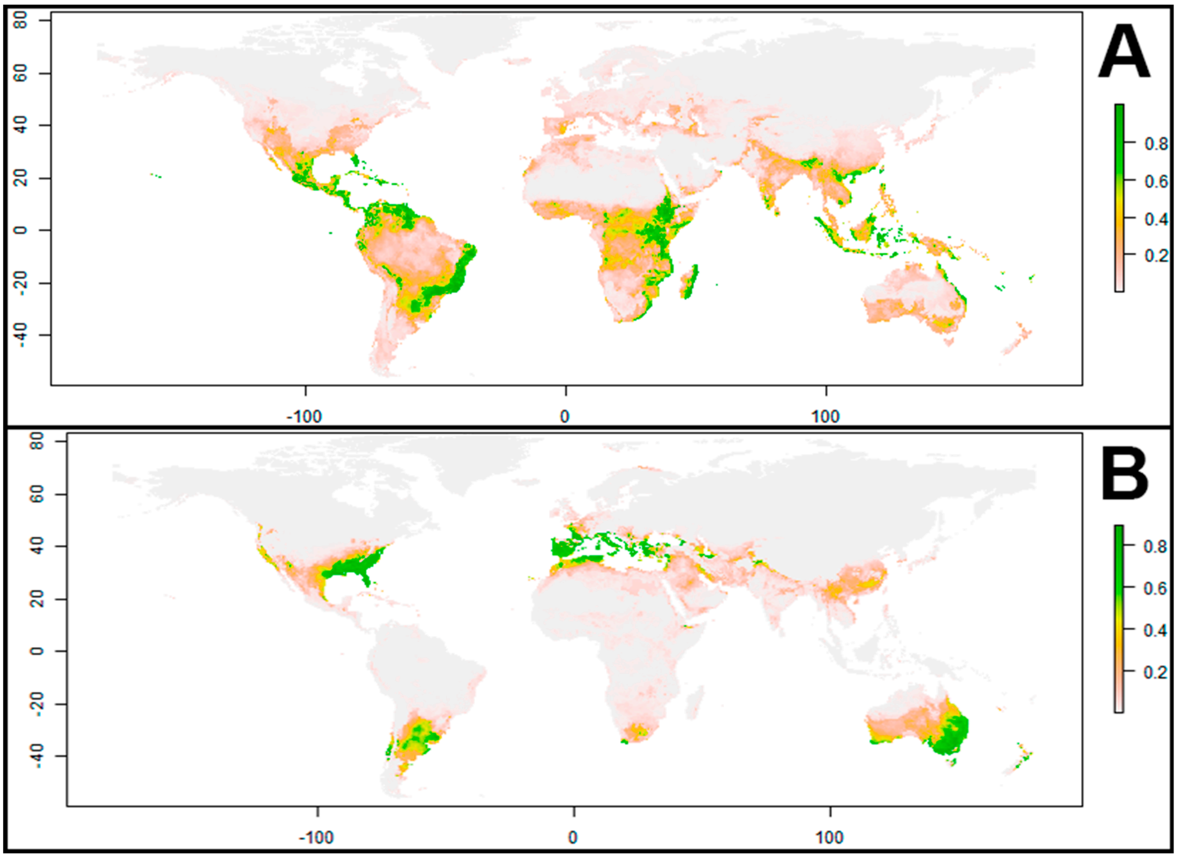

Figure 6. Result of the analysis of binomial tests (CliMond 2090 (2081–2100) [30]): (**A**)—*P. reticulata*; (**B**)—*G. holbrooki*.

4. Discussion

As a result of GIS modeling, climatic factors have been identified that allow new invasive alien species to inhabit southern Europe in the future. The new perspectives in Eastern Europe are very different from the conditions of the ecological niche of the native range of these fish species (Figure 3). However, due to increasing effects of climate change (to 2090; Figures 4B and 5B) and the emergence of "synanthropic ecological niches" in anthropogenic territories [36], these new perspectives provide great opportunities for the naturalization of invasive alien thermophilic poikilothermic animals with their own viviparity strategy. Under such conditions, not all native species will be able to survive in the changing climatic conditions under the influence of anthropogenic pressure [37]. In the more northern regions of Eastern Europe in a changing climate such invasive alien thermophilic fish species will not compete directly with the native ichthyofauna in the nearest future, as in very warm drains in anthropogenic territories or during mass summer fish kills, most of the native fish species die [1]. Instead, they can occupy their niche in new habitats, having an important role in ecosystems and for biological control (especially in anthropogenic areas) in a changing climate. It should be noted that in the so-called "warm countries" of Europe and other parts of the world where these two species are invasive, they can pose a threat, particularly mosquitofish, by consuming eggs of fish and amphibians of the 'Critically Endangered (CR)' yellow-spotted tree frog (see *Litoria castanea* in IUCN Red List of Threatened Species); the 'Endangered (EN)' green and gold frog (see *Litoria raniformis* in IUCN Red List of Threatened Species); and the 'Vulnerable (VU)' golden bell frog (see *Litoria aurea* in IUCN Red List of Threatened Species) [38]. Taking into account mouth size and ability to switch to a more zooplanktivorous diet under certain conditions [12,39–41], it is quite likely that in the northern regions such species can possibly become an additional threat for amphibian species native for Northern Europe, feeding on eggs and tadpoles/larvae of oriental tree frogs *Hyla orientalis* (Bedriaga, 1890), fire-bellied toads *Bombina bombina* (Linnaeus, 1761), crested newts *Triturus cristatus* (Laurenti, 1768) and common newts *Lissotriton vulgaris* (Linnaeus, 1758). It was confirmed by some studies [42] that in countries with warmer climate these alien invasive fish species can become a threat to native ichthyofauna, competing with aboriginal species for food resources, feeding on phyto- and zooplankton (cladocerans, copepods, ostracods, rotifers and insects) decreasing feeding base for native species and damaging already established food chains. Therefore, their potential impact on aboriginal biota in terms of changing climate conditions should not be underestimated.

5. Conclusions

We determined the bioclimatic variables influencing the expansion of the area of these two invasive alien fish species, which will allow them to occupy their special niche in anthropogenic territories of Southern Europe. As a result of GIS modeling of collected data, it was found out that by 2090 expansion of these species to Eastern Europe is highly likely. The appearance of guppies in the south of Ukraine is possible (the estuary of the Danube river, as well as in several parts of the Caucasus, Turkey, lower part of the Don river (>0.3–0.5, Figure 4). *G. holbrooki* will also slightly expand its range in Europe, the Caucasus as well as in Ukraine, namely in the Crimean peninsula, western part of the Black Sea region and the Danube estuary (Figure 5). The results obtained showed that *P. reticulata* are more attached to warm drains than *G. holbrooki* and the quality of water seems not affecting its distribution.

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Data Availability Statement: The data presented in this study are openly available in [*Gambusia holbrooki* Girard, 1859 in GBIF Secretariat (2021); GBIF.org (2 April 2021) GBIF Occurrence Download at https://doi.org/10.15468/dl.d5e6w9, accessed on 2 April 2021], reference number [23] and *Poecilia reticulata* Peters, 1859 in GBIF Secretariat (2021); GBIF.org (16 June 2021) GBIF Occurrence Download at https://doi.org/10.15468/dl.tuwazq, accessed on 16 June 2021, reference number [24].

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