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Prediction of Current and Future Suitable Habitats for Three Invasive Freshwater Fish Species in Europe

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Abstract: Climate change can have a significant impact on the Earth's ecosystems. Invasive species will respond to climate change, and their responses will have ecological and economic implications. Habitat suitability models (HSMs) are some of the most important tools currently available for assessing the potential impacts of climate change on species. The projections of a model of suitable conditions for three invasive fish species in Europe, *Lepomis gibbosus*, *Perccottus glenii* and *Pseudorasbora parva*, built using Maxent and based on the occurrence throughout the range (native and invasive), on the current climate of Europe and on the forecast climate data for the 2050s and 2070s in the SSP2 and SSP5 scenarios are presented herein. For *Lepomis gibbosus* and *Pseudorasbora parva*, climate change will lead to a significant expansion of their zones, with suitable conditions to the north and east, while the change in suitability in their existing ranges will be moderate. For *Perccottus glenii*, the zone with suitable conditions will shift northward, with a gradual deterioration in the southern and central parts of its current range and an improvement in the northern part. Thus, at present and until the 2070s, *Lepomis gibbosus* and *Pseudorasbora parva* can be considered potentially dangerous invasive species in most parts of Europe, while *Perccottus glenii* can be considered as such only in the northern part of Europe.

Keywords: maxent; HSM; SDM; Europe; climate change; alien species; *Lepomis gibbosus*; *Perccottus glenii*; *Pseudorasbora parva*

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Citation: Artaev, O. Prediction of Current and Future Suitable Habitats for Three Invasive Freshwater Fish Species in Europe. *Water* **2023**, *15*, 2091. https://doi.org/10.3390/w15112091

Academic Editor: Evgeniy S. Gusev

Received: 21 April 2023
Revised: 21 May 2023
Accepted: 30 May 2023
Published: 31 May 2023

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1. Introduction

Climate change can have a significant impact on the Earth's ecosystems [1–3]. In addition to direct effects on habitat quality, climate change will foster the expansion of invasive species into new areas and magnify the effects of invasive species already present [4]. Habitat suitability models (HSMs) are some of the most important tools currently available for assessing the potential impacts of climate change on species [5,6].

Maxent is a software package developed for modeling species distributions given presence-only species records and a "background" sample of environments in the region of interest [7–9]. The method is based on the search for patterns in the distribution of environmental factors at points with proven species habitations. The most popular result output method is cloglog (from 0 to 1), which should rather be interpreted as the relative suitability of environmental conditions [9]. With the easy availability of presence-only occurrence data [10], the well-established Maxent algorithm [11–13], and the possibility applying (projecting) the resulting model (normalized exponential function) to any territories or time periods (if they have the same predictors) [14–16], as well as availability of climate data for future conditions [17], it is possible to assess the potential impact of climate change on species in the future.

The purpose of the work is to suggest how climate change may affect the distribution of suitable conditions for three invasive fish species in Europe. A model of suitable conditions for the species is built on the basis of occurrences throughout the range (native and invasive), and it is projected onto forecast climate data for the 2050s and 2070s in the SSP2 and SSP5 scenarios.

Of the dangerous invasive fish species in Europe, we have selected three whose HSMs can claim maximum credibility due to the following features. The species have wide ranges in regions with well-defined gradations of climatic conditions, allowing for a better assessment of their contribution to the distribution [18]. These three species do not have closely related native lineages in Europe from the same families, which makes them easily recognizable and gives more credibility to occurrences provided in published sources.

Lepomis gibbosus (Linnaeus 1758) (Perciformes: Centrarchidae) was introduced into Europe from North America in the late 19th century [19] and has now become widespread in Europe. Its aggressive behavior, especially from small individuals, endangers local fish, amphibians [20], and invertebrate fauna [21]. *Perccottus glenii* Dybowski 1877 (Perciformes: Odontobutidae) has a native range in the Far East of Russia, in China, and in North Korea. Since 1916, initially with the help of aquarists, and the middle of the 20th century, due to the distribution of Far Eastern aquaculture fish, the species has spread to Central and Eastern Europe [22]. Due to its high ecological plasticity, it inhabits small bodies of water, where it causes a catastrophic decrease in the species diversity of large forms of invertebrates, fish, and amphibians [23,24]. The penetration of *P. glenii* into fish ponds can cause a decrease in the profitability of fish farms [25]. *Pseudorasbora parva* (Temminck & Schlegel 1846) (Cypriniformes: Gobionidae) has a native range in the Far East, mostly within China, Taiwan, Korea, and Japan. Introduced into Romania in the early 1960s, *P. parva* has invaded the freshwaters of almost every country in Europe and the adjoining parts of Asia [26]. By feeding on the larvae of native fish, it reduces their numbers [27], and it can cause damage to juveniles of farmed commercial fish species at high levels of abundance [28]. It is an asymptomatic carrier of pathogens of a number of viral, fungal, and parasitic fish diseases [24].

The distribution of suitable conditions modeled for the current climate relative to the current ranges of the species, changes in their distribution and areas of suitable conditions in the future, changes in the conditions of current populations in the future, as well as the contributions and importance of predictors in the model are analyzed. To create and project models, we took into account recommendations and best practices [29–32], used the latest climate models available, and tried to present the result in the most convenient form for further use and analysis.

The operating tiff files presented herein allow for the assessment of threats in certain territories, the identification of zones with better conditions that are potentially more dangerous in terms of the spread of invasive species, and the analysis of the dynamics of relative suitability of the environmental conditions in certain areas. The stakeholders can be local governments, organizations working in the field of nature conservation, and fisheries.

2. Materials and Methods

2.1. Study Area

The range of species is located in the northern hemisphere. The native range of *P. parva* and *P. glenii* is located in the east of Eurasia [33,34], and the native range of *L. gibbosus* is in North America [19]. In Europe, all three species have an introduced range. In order to better cover the conditions for building models, we used occurrences from both the native and introduced ranges (Figure S1_1); however, here, we consider only part of the range limited by Europe and the close, adjacent freshwater ecoregions (The Atlantic basin of Asia Minor and the basins of the Kura and Ural rivers) [35] which form one macro-region with relatively natural freshwater boundaries.

2.2. Environmental Data

Although habitat conditions are determined by many factors, as well as their combination, an analysis of habitat suitability and even species distribution based on bioclimatic factors using the Maxent algorithm has proven itself well [12,13,30]. To improve the accuracy of model for its construction and projection into the future, we added two geomorphological

predictors that contribute significantly to the distribution of hydrobionts [36–39]—altitude and terrain slope.

Climate data for 1979–2013 [40] were used to model suitable conditions in the present time, provided by Paleoclim [41]. For forecasting, we used downscaled CMIP6 projections [17] provided by WorldClim [42]. For both cases, we used GMTED2010 altitude data [43], as well as terrain slopes calculated on their basis. All data have a spatial resolution of 30 s.

Of the 5 Shared Socioeconomic Pathways scenarios, we chose 2: SSP2 (intermediate GHG emissions) as the most probable and SSP5 (very high GHG emissions) as the most extreme scenario [44]. From 25 initially available global climate models (GCMs), we selected 5 GCMs which are considered the most suitable for Europe, CanESM5, CNRM-CM6-1, HadGEM3-GC31-LL, MIROC6, and MPI-ESM1-2-LR [45], and used the average values of ensemble GCMs. For the future HSM projection, we chose two time intervals, 2041–2060 (for brevity—the 2050s) and 2061–2080 (the 2070s), considering that more distant forecasts are less accurate.

2.3. Species Occurrence Data

The wide distribution and great abundances of the species, as well as their ease of recognition, made it possible to accumulate a large number of occurrences that are necessary for building models.

We used occurrences from GBIF and from the literature [34]. The occurrences from GBIF were cleaned up: occurrences with the status "Absent", with empty coordinates, and with a coordinate uncertainty of more than 1000 m were removed. The occurrences used to build the final model are shown in Figure S1_1. We used 533 occurrences for *L. gibbosus*, 139 for *P. gleniii*, and 289 for *P. parva*.

2.4. Data Preparation, Model Building, and Evaluation

Maxent v. 3.4.4 [46] was used for modeling habitat suitability from presence-only species records. We used a 10-fold cross-validation procedure to test the models. The average of these 10-fold procedures was used as the model result. The jackknife test was used to identify the important variables [47]. Maximum entropy modeling was carried out using default parameters, including 10,000 background sites, an iteration of 500 times, "auto-feature" as the adjustment method for parameter regularization, and "1" as the value of the regularization multiplier (beta value).

With a lack of detailed biological knowledge of focal species, simpler predictor datasets produce models that are more accurate than those calibrated using comprehensive bioclimatic datasets [11,31]. With over 400 parameters tested, precipitation and temperature have been shown to be the most important environmental variables in species distribution modeling [48]. Although Maxent is highly robust to the effects of predictor collinearity during model calibration [49], for better model transferability [31], we removed highly correlated predictors (Pearson's $r > 0.8$) (Table S1_1) using ENMTools v. 1.3 [50]. Thus, from the bioclimatic variables, we left 3 variables characterizing temperature (Bio_1—annual mean temperature, Bio_5—maximum temperature of the warmest month, and Bio_6—minimum temperature of the coldest month) and 3 variables characterizing humidity (Bio_12—annual precipitation, Bio_14—precipitation of the driest month, and Bio_15—precipitation seasonality). In the Maxent model, we only used only data for the northern hemisphere. The percentage contribution and permutation importance values for these variables to the final (r100b2000) MaxEnt models are shown in Table 1.

The reliability of the future predictions was verified by performing a multivariate environment similarity surface (MESS) analysis [51] (Figure S1_2). These analyses quantify the climatic similarity between current and future environments across the target region, assigning negative values to areas that will be climatically dissimilar and positive values to areas that will be climatically similar.

Table 1. Percentage contribution and permutation importance values of the predictor variables to the final (r100b2000) MaxEnt models.

Variable	Percent Contribution	Permutation Importance
Lepomis gibbosus		
Annual Mean Temperature (Bio_1)	50.3	51.8
Annual Precipitation (Bio_12)	15.6	11.6
Precipitation of the Driest Month (Bio_14)	13.7	6.4
Max Temperature of the Warmest Month (Bio_5)	6.9	6.3
Altitude	4.7	8.3
Precipitation Seasonality (Bio_15)	4.6	2.4
Slope	2.3	1.9
Min Temperature of the Coldest Month (Bio_6)	2.1	11.3
Perccottus glenii		
Max Temperature of the Warmest Month (Bio_5)	23.4	32.1
Annual Mean Temperature (Bio_1)	21.4	20.7
Annual Precipitation (Bio_12)	19.9	1.9
Slope	18.1	3.1
Altitude	9.7	18.7
Min Temperature of the Coldest Month (Bio_6)	5	12.6
Precipitation Seasonality (Bio_15)	1.9	6.1
Precipitation of the Driest Month (Bio_14)	0.5	4.6
Pseudorasbora parva		
Annual Mean Temperature (Bio_1)	39.2	52
Precipitation of the Driest Month (Bio_14)	23.6	3.7
Annual Precipitation (Bio_12)	14.4	16.1
Max Temperature of the Warmest Month (Bio_5)	7.7	3.8
Altitude	7.6	6.8
Min Temperature of the Coldest Month (Bio_6)	5.3	14.4
Slope	1.8	1.2
Precipitation Seasonality (Bio_15)	0.3	1.9

To access model transferability and the overall performance of the final selected models, we used metrics that evaluate predictive accuracy (Table S1_2). AUCs, OR10, and maxSSS values were calculated by Maxent. The threshold-independent CBI (continuous Boyce index) was calculated in R using the ecospat package [52]. For its calculation from a general set of occurrences, we excluded those on which the model was built. The AUC (area under the curve) is a threshold-independent measure of predictive accuracy based only on the ranking of locations. The AUC is interpreted as the probability that a randomly chosen presence location is ranked higher than a randomly chosen background point [53]. The values of the AUC range from 0 to 1 in which 1 indicates the model's perfect ability to differentiate between presence and background points and 0.5 indicates random-level discrimination [54]. The threshold-dependent TSS (true skill statistic) was calculated in MS Excel using the formula sensitivity + specificity − 1 [55]. TSS values vary from −1 to 1 and follow grades similar to that of the kappa statistic: −1 to 0.40 = poor quality, 0.40 to 0.55 = fair quality, 0.55 to 0.70 = good quality, 0.70 to 0.85 = very good quality, and 0.85 to 0.99 = excellent quality [56]. The maxSSS threshold, which is considered to produce the best results for models based on presence-only data [57], was used to calculate the TSS. However, since the species are invasive, we used a lower threshold: OR10 (or 10TP, 10% training presence test omission rate) to classify suitable habitats by categories. This threshold selects the value above which 90% of the training locations are correctly classified. MaxEnt provides four output transformations for model values in raw, cumulative, logistic, and log-log (cloglog); these output formats are monotonically related to each other. The cloglog provides an estimated value between 0 and 1 of the probability of presence, with higher values demonstrating more favorable conditions. We classified the cloglog output format for suitable habitat areas into four levels: "unsuitable" (0-OR10), "lowly suitable" (OR10-0.6), "moderately suitable" (0.8–0.6), and "highly suitable" (0.8–1).

In order to avoid autocorrelation, 3 options to spatially rarefy the occurrence data (used the tool Spatially Rarefy Occurrence Data for SDMs in SDMtoolbox Pro v0.9.1 for ArcGIS Pro [58,59]) were chosen: 50, 100, and 200 km (named r50, r100, and r200 in the model, respectively). In addition, to avoid sampling a habitat greatly outside the known occurrence of a species [60], we chose 3 options for the bias file—buffers at 100, 500 and 1000 km from the points of occurrence (named b100, b500 and b1000 in the model, respectively) (we used the tool Sample by Distance from Obs. Pts. in SDMtoolbox Pro v0.9.1 for ArcGIS Pro [58]). Thus, we built 9 models for each species (Table S1_2). To select the best model, we focused primarily on the AUC test, AUC diff, CBI, and TSS indexes [31].

The highest and comparable values of the evaluation metric were demonstrated by the models r50b2000 and r100b2000 (Table S1_2). However, in order to avoid autocorrelation, considering that the distribution of occurrences does not fully reflect species distribution, we chose models built with a wider rarefaction (r100b2000). We then continued to work with these models and projected them onto the future climate.

The selected models (r100b2000) for each species were projected over two time intervals, 2041–2060 (2050s) and 2061–2080 (2070s), onto climate forecasts, according to two scenarios (SSP2-4.5 and SSP5-8.5).

To understand how climate change will affect known habitats, we considered how conditions will change in these habitats in the future, using for this analysis the same occurrences on the basis of which the models were built (rarefied with a resolution of 100 km).

3. Results

3.1. Distribution of Suitable Conditions for Lepomis gibbosus and Possible Future Changes

3.1.1. Current Distribution of Suitable Conditions

The current range of *L. gibbosus* in Europe occupies a smaller area than its suitable habitats (Figure S2_Le1). The territory with suitable habitats that are currently not inhabited by *L. gibbosus* includes most of the territory of Poland, the northern part of Ukraine, the Kuban region, the foothills and flat areas of Caucasus and Transcaucasia, the central part of Great Britain, Ireland, the southeastern part of Baltics, and most of Asia Minor, especially the western and coastal regions. The suitable conditions for the species in the area under consideration are wider than its current range.

3.1.2. Potential Changes in Suitable Conditions in Europe in the Future

The climate change scenarios assume a significant expansion of the suitable conditions in a northern direction and, depending on the scenario, a slight or moderate decrease in the south (Figure S2_Le2–S2_Le5). By the 2050s, even in the intermediate SSP2 scenario, suitable conditions will already be found in Belarus, in the Baltic region (excluding the northern part of the Gulf of Bothnia), and in the west and center of the European part of Russia, and separate foci will appear in the Southern Urals. By the 2070s, in the same scenario, areas with suitable conditions in the Southern Urals will increase significantly, and the northeast border of the suitable conditions will pass through the Russian regions of Perm, Kirov, Vologda, and southern Karelia. At the same time, conditions will worsen in the south and east of the Iberian Peninsula, in the southern Balkans, and in southern Asia Minor.

According to the most extreme SPP5 scenario, the zone with suitable conditions will shift significantly to the north and will be located north of the Pyrenees, Alps, and Carpathians, and further east, the southern border will pass along the north of the Dnieper and Don basins, along the Middle Volga and Kama. In the north, the conditions will be suitable in the entire Baltic basin, including the drainage of the Gulf of Bothnia, Karelia, the Northern Dvina basin, and the southern part of the Pechora basin.

Projected climate change may contribute to an increase in the area with suitable conditions from the current 7.69 million sq. km to 2 million sq. km by the 2070s in the most probable SSP2 scenario or to 2.4 million sq. km in the most extreme SSP5 scenario

(Figure 1). However, most of the territory will be represented by moderately and lowly suitable conditions.

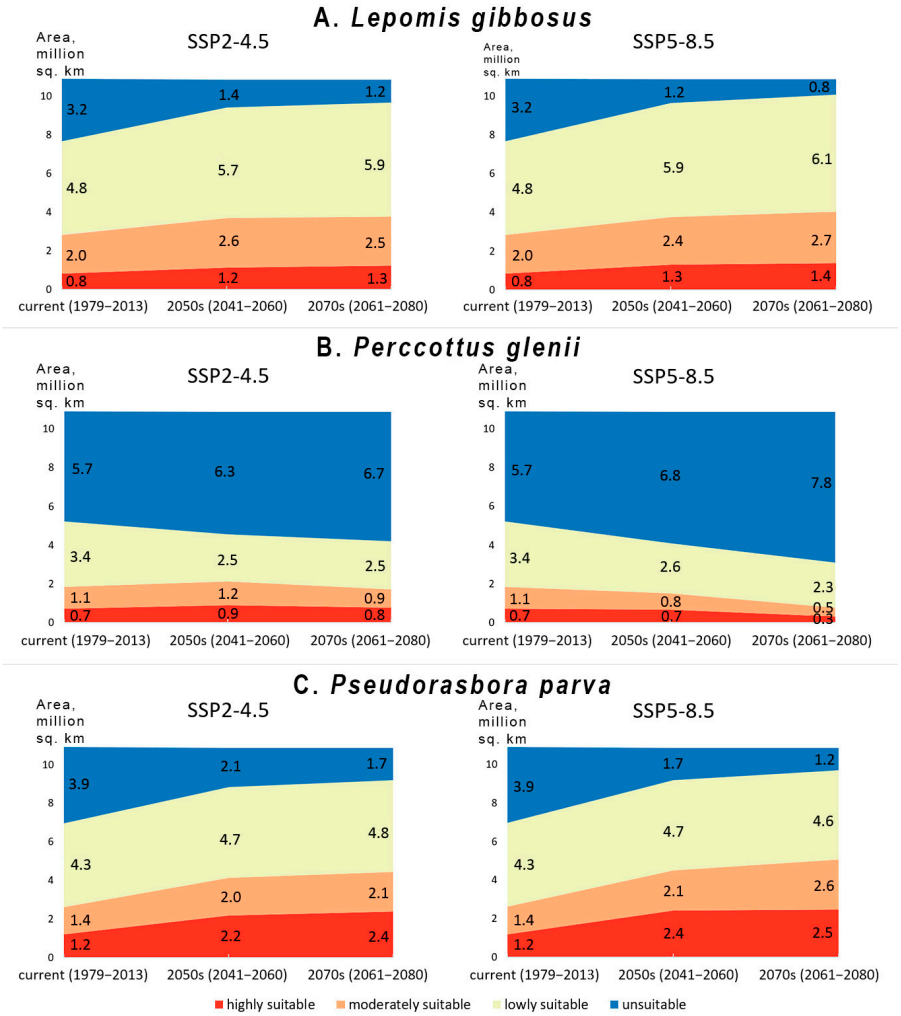

Figure 1. Possible changes in the areas with suitable habitats in the study area in two scenarios (SSP2 and SSP5) until the 2080s.

3.1.3. Potential Changes in Suitable Conditions in Current Habitats

As described above, climate change will contribute to the expansion of the range to the north, and with the most significant changes (SSP5), the conditions in southern Europe, where the species is now widespread, will begin to shift for the worse by the 2070s. Climate change will have a slight negative impact on existing populations, which will be more pronounced in the SSP5 scenario and will be expressed as an increase in the proportion of habitats with lowly suitable conditions (Figure 2).

3.1.4. Influence of Predictor Variables

For the Maxent model, the annual mean temperature and annual precipitation are of the greatest importance, with the largest contribution of the first predictor (Table 1, Figure S3_1) predicting the probability of an occurrence greater than 0.5 at an average annual temperature of 6–20 degrees (Figure S3_2). The smallest relative contributions for the model are the maximum temperature of the warmest month and the precipitation seasonality. Geomorphological predictors do not have a significant importance in the model, and if probability of occurrence is higher than 0.5 at an altitude below 1200 m above sea level, then the slope practically does not matter.

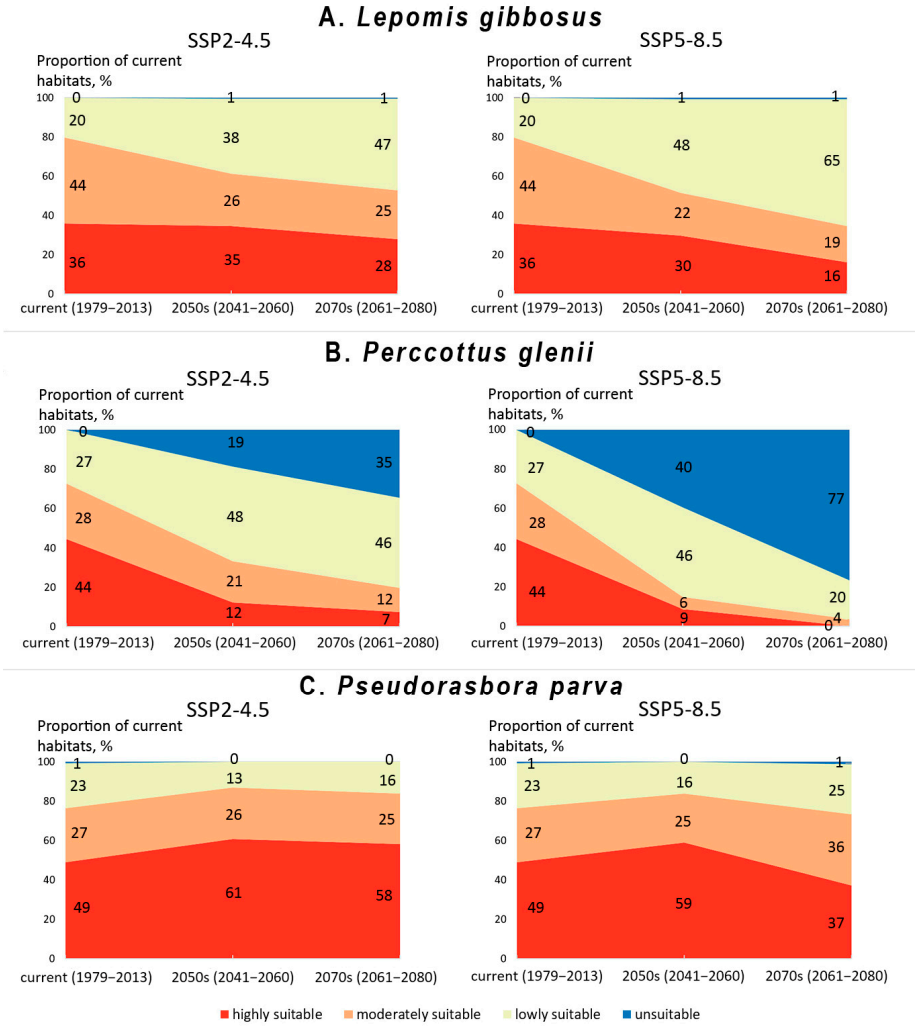

Figure 2. Possible changes in the proportions of current habitats (occurrences) by suitability areas for two scenarios (SSP2 and SSP5) until the 2080s.

3.2. Distribution of Suitable Conditions for Perccottus glenii and Possible Future Changes

3.2.1. Current Distribution of Suitable Conditions

The current distribution of the species is limited to central and eastern Europe, and it is absent in both the north and south of Europe. The suitable conditions actually form a strip running through the center of the European part of Russia, northern Ukraine, Belarus, Poland, and north-eastern Germany (Figure S2_Pe1). Based on our model, the currently suitable conditions outside the current range are in the lowlands adjacent to the Peipsi and Ilmen lakes, the lowlands along the Northern Dvina, the Lake Mälaren basin in Sweden, and the North German Lowland.

3.2.2. Potential Changes in Suitable Conditions in Europe in the Future

Climate change will significantly shift suitable conditions northward. By the 2050s, according to the intermediate SSP2 scenario, the southern part of modern range will already be in a zone with unsuitable conditions (Figure S2_Pe2). According to this model, suitable conditions will be found in the entire eastern Baltic and the coastal regions of the Baltic Sea, in Karelia, in the southeast of Scandinavia, the northern part of Volga basin, in the Northern Dvina and Mezen basins, and, to a lesser extent, in the Pechora basin. By 2070s, in the same scenario, the zone with suitable conditions will also continue to move north (Figure S2_Pe3). Similar areas with suitable conditions are predicted to exist by the 2050s in the more severe SSP5 scenario (Figure S2_Pe4) and, by the 2070s, suitable conditions

will be located along the coast of the Barents and White Seas and in Karelia, Finland, and Northern Sweden (Figure S1_Pe5).

In the territory under consideration, by the 2070s, the SSP2 scenario could lead to a decrease in the area of the territories with suitable conditions from the current 5.2 million sq. km by 1 million sq. km. Alternatively, in the more extreme SSP5 scenario, the decrease in area will be more significant: a decrease of 2.2 million sq. km (Figure 1).

3.2.3. Potential Changes in Suitable Conditions in Current Habitats

Considering that areas with suitable conditions will be significantly shifted to the north, most of the current habitats will be in a zone with unsuitable conditions (Figure 2). Additionally, in the moderate SSP2 scenario, by the 2070s, 35% of the current habitats will be in a zone containing unsuitable habitats, and in the more extreme SSP5 scenario, 77% of the current habitats will be in a zone containing unsuitable habitats.

3.2.4. Influence of Predictor Variables

Of the bioclimatic factors included in building the model, the most important predictors were the maximum temperature of the warmest month and the annual mean temperature (Table 1, Figure S3_1). The maximum probability of occurrence is clearly fixed at a temperature of 24–25, and below 15 and above 24 it approaches 0. In addition, a rather high response is given by the annual mean temperature. The terrain predictors slope and elevation contribute significantly to the model (Table 1, Figure S3_1), with a probability of occurrence of above 0.5 in places with a slight slope (up to 5 degrees) and a height of up to 600–700 m above sea level (Figure S3_3). Among the considered predictors, precipitation (precipitation seasonality and the precipitation of the driest month) and the minimum temperature of the coldest month had the least value for model, confirming the known ecological features of the species—the ability to survive after freezing into ice and experiencing habitat drainage [61,62].

3.3. Distribution of Suitable Conditions for Pseudorasbora parva and Possible Future Changes

3.3.1. Current Distribution of Suitable Conditions

In Europe, this species is widely distributed, with the exception of the Iberian Peninsula (where few occurrences are known along the southern coast), Northern Great Britain, the islands of the Mediterranean Sea, and southern Greece. The eastern border of the range currently passes through the basins of the Vistula, Dnieper, Don, Kuban, and Terek. Suitable conditions outside the current range in Europe are currently found in Northeast Germany, in the Kaliningrad region, and in the south of the European part of Russia (Figure S2_Ps1).

3.3.2. Potential Changes in Suitable Conditions in Europe in the Future

Climate change will lead to a significant expansion of territories with suitable conditions. According to the intermediate SSP2 scenario, by the 2050s, suitable conditions will be found in the east of Poland, in Belarus, in the Baltics, in the western regions of Central Russia, and in the south of Sweden and Finland (Figure S2_Ps2). By the 2070s, the central and western parts of the Volga basin will be added to the territories with suitable conditions (Figure S2_Ps3). The same territories will have suitable conditions in the SSP5 scenario by the 2050s (Figure S2_Ps4). By the 2070s, according to the SSP5 scenario, the eastern boundary of suitable conditions will pass along the Volga and Northern Dvina basins, and in the north, it will be limited by Karelia, southern Finland, the coastal part of the Gulf of Bothnia, and southern Sweden. Great Britain and Ireland will be entirely in the zone with suitable conditions. In the south of Europe—in Spain, Greece, and Turkey—the suitability of the conditions will deteriorate slightly. The conditions in northeast Kazakhstan are unsuitable, both at present and until the 2070s, even in the SSP5 scenario.

By the 2070s, climate change could lead to an increase in the area with suitable conditions from the current 7 million sq km by 2.2 million sq km in the SSP2 scenario or by 2.7 million sq km in the SSP5 scenario (Figure 1).

3.3.3. Potential Changes in Suitable Conditions in Current Habitats

The projected climate changes will lead to a non-linear change in the degree of suitability of the current habitats (Figure 2). In both scenarios (SSP2 and SSP5), by the 2050s, the number of habitats in the zone with highly suitable conditions will slightly increase, and if there are no significant changes by 2070s in the SSP2 scenario, then in the SSP5 scenario, the percentage of habitats in the zone with highly suitable conditions will decrease significantly. However, climate change will hardly lead to the deterioration of conditions such that they become unsuitable.

3.3.4. Influence of Predictor Variables

The most significant predictors, as for *L. gibbosus*, are the annual mean temperature, the precipitation of the driest month, and annual precipitation (Table 1, Figure S3_1). The probability of an occurrence above 0.5 in the range of the annual mean temperature is about 8–23 degrees, and the maximum temperature of the warmest month is about 19–36 degrees (Figure S3_3). The importance of geomorphological predictors in the model is low, and altitude has a slightly larger value than slope.

4. Discussion

Changes in suitable conditions may affect the ranges of species in the future. In the case of the deterioration of conditions, a species may begin to adapt to changing environmental conditions, and how its abundance and distribution will change depends on the success of this process [63]. Improvements in environmental conditions for a species in areas where it is currently absent may be an advantage to the formation of populations and its further distribution there.

For each species, we built nine models by combining three options to rarefy occurrences (50, 100, and 200 km), and the sizes of the areas from which Maxent took background or pseudo-absence points (Bias files) were areas bounded by radii of 500, 1000, and 2000 km around the occurrences. Using rarefaction with small distances, we risked incurring the effect of autocorrelation, when the density of occurrences would not reflect the true distribution of the species but would rather reflect places that were explored more. Using large values, we risked reducing the accuracy of the model. Limiting the areas in which Maxent needed to select pseudo-absence points allowed the model to avoid their selection from a habitat far outside the known habitat of a species. Of the nine models obtained for each species, the models with a bias value of 2000 km and rarefaction values of 50 and 100 km had the best estimates (Table S1_2). However, considering that even with a rarefaction of 50 km, the observations would not be able to reflect the distribution of the species on a global scale, we chose models with a rarefaction value of 100 km.

For modeling, we used occurrences from the native and invasive ranges [64]. Models built separately for native and invasive species often have differences that indicate a shift in the realized niche in the invasive area [65–67]. Considering that the distribution of a species in nature actually reflects its realized niche, which is less than the fundamental one under the influence of biotic and abiotic environmental factors [68], these differences may be due to factors not taken into account by the model. In addition, taking into account the success of applying the main abiotic (bioclimatic) factors in modeling species distribution, it can be assumed that the factors not taken into account by the model may include abiotic factors that are independent of the widely used bioclimatic factors, as well as biotic factors. Thus, we assumed that a shift in the occupied niche in the invasive part of the range lies within the tolerance of the bioclimatic factors on which the model is based; this is in agreement with researchers that models using both native and invasive occurrence points together to predict the spread of an invasive species are generally more accurate at predicting the extent of the spread and the pattern of risk for invasive distributions [69,70].

Lepomis gibbosus. The positive impact of climate warming on the species has been proven both experimentally and through the application of AS-ISK [71–73]. A comparison of the niches of the natural and invasive ranges confirmed that it has significantly modified

its niche in the process of its invasion into Europe, highlighting the great adaptability of this species to higher temperatures and irregular water regimes [74].

Modeling of the range expansion of *L. gibbosus* was carried out for Latvia and Ukraine based on 598 observations in Europe (invasive part of the range) and 18 environmental variables [75]. A qualitative analysis of the suitability of the conditions was carried out; however, in our opinion, there are signs of overfitting in the presented model—a high variability in the suitability of habitats in a relatively small area.

According to the model suggested herein, at present, the suitable conditions for the species in Europe are wider than its range, primarily in the eastern and northeastern directions. This is probably due to the influence of North American occurrences on the model in areas the species inhabits, including in areas with colder conditions [74]. It is possible that these territories can already be considered the most at risk for invasion at the present time. (Figure S2_Le1). With the predicted climate changes, territories with suitable conditions will be significantly increased in the northern and eastern directions, while conditions in southern Europe, Turkey, and the Caucasus will change in a negative direction. With moderate climate change (SSP2 for the 2050s and 2070s and SSP5 for the 2050s), Belarus, the central, western, and southern parts of the northwestern regions of Russia, the southern Urals, southern Sweden, and southern Finland will join the current zone with a high risk of successful invasion. The deterioration of suitable conditions is predicted for Spain, Greece, Bulgaria, and Turkey, as well as the Caucasian countries (Figure S2_Le2–S2_Le4). With a more significant degree of climate change (SSP5 for 2070s), the predicted suitable conditions greatly expand to the north and will have a southern boundary along the western line and northern coast of the Iberian Peninsula—from the Pyrenees, Alps, and Carpathians to the middle reaches of the Dnieper, the upper reaches of the Don, the middle reaches of the Volga, and to the Southern Urals. In the north, the Scandinavian Mountains, the Kola Peninsula, and the polar Urals, as well as the territories adjacent to the Barents Sea west of the Kanin Nos Peninsula, will remain a zone with unsuitable environmental conditions.

Climate change will lead to a significant increase in the area comprising territories with suitable conditions. Existing populations will be affected by climate change, primarily through a shift in conditions from highly and moderately suitable to lowly suitable. Populations from the southern part of the modern range will have more exposure to this. More severe scenarios (SSP5) assume the acceleration of these processes.

Perccottus glenii. Earlier, there were attempts to model the potential range of *P. glenii* using the Maxent method based on occurrences in its native and invasive ranges [34]. In general, the results of the published model are consistent with ours with the exception of Western Europe. The differences are probably due to the difference in the factors used, as the authors took into consideration the growing degree of days above 10 °C and the mean ratio of the annual actual over potential evapotranspiration. Unfortunately, having built a model using these factors, we will not be able to project it onto future forecasts because we do not know the predictions of these factors.

Modeling the suitable conditions for the species was carried out in comparison with species that may affected by *P. glenii*, using two species of native newts in Latvia [76], where the model was projected onto the climate of the future. The presented models have a number of common features (unsuitable conditions in the north, south, and west of Europe for a model projected onto CliMond data from 1975, and a northward expansion when projected onto 2050 data) and differences (weaker northward shift of suitable conditions) with the results presented in this paper. The differences are probably due to the authors' use of earlier climate data (MIROC-H vs. SSP), as well as a different set of occurrences. For the natural range of the species, there is a significant lack of occurrences among the published data in the literature and GBIF with the exception of the source [34], which was probably not used by the authors.

The model based on the current distribution of a species assumes a narrower distribution of suitable conditions than other two species considered. (Figure S2_Pe1). The most

suitable conditions are currently concentrated in the basin of the middle and upper Volga, the upper Don, the upper and middle Dnieper, and the river basins of the southern and eastern Baltics. Terrain factors are more important for the *P. glenii* model than for other species considered, as it prefers reservoirs with stagnant or slowly flowing water [61,77].

Climate change will cause a significant shift in the entire zone with suitable conditions to the north (Figure S2_Pe2–S2_Pe5). In general, climate change will negatively affect the habitat conditions of the species in Europe. This will be expressed as an overall reduction in the area with suitable conditions (Figure 1) and its significant shift to north, as a result of which more existing populations will cover a zone with unsuitable conditions (Figure 2). Thus, with a more significant climate change (SSP5 for the 2070s), about 77% of the current populations will be in a zone with unsuitable conditions (Figure 2). Based on this, it can be expected that changing conditions will force the species to adapt, especially in the southern part of the current range, which may lead to a decrease in the size of the populations or its extinction. On the contrary, improving conditions in the north, may lead to an increase in the size of existing populations and the expansion of its range. Considering the predisposition of the species to small bodies of stagnant water, which are rich in floodplains, its distribution vector will be associated with them [34,77].

Perccottus glenii and *Lepomis gibbosus*

Attempts to build a distribution model for this species using Maxent have already been made [78]; however, the occurrences in Eastern Europe were not taken into account, and based on the materials and methods, spatially rarefied occurrence data were not held, which could affect the autocorrelated occurrence point. However, the general pattern has a certain similarity with those proposed in this paper.

The model assumes a high suitability of conditions outside the current range, primarily in northeastern Germany and northwestern Poland. A large population of the species exists in the Upper Don basin; however, the model suggests a low level of suitability of the conditions here.

In general, climate change will positively affect conditions for the species in Europe. Area of territories with suitable conditions will increase (Figure 1); at the same time, conditions for the current populations under the influence of moderate climate change (SSP2 for 2050–2070 and SSP5 for the 2050s) will improve, and with more significant climate change (SSP5 for the 2070s), there will be a tendency to worsen (Figure 2). Conditions will improve primarily in the Baltics, Belarus, southern Russia, Ireland, and the northern part of the Great Britain. Then, conditions will improve in the west of the Central part of Russia, in South Sweden, and in Finland, and in the most extreme scenario (SSP5 for the 2070s), in addition to the above, conditions will be suitable in almost the entire basin of the Volga, in the Northern Dvina, in southern Karelia, northern England, and even Norway on the coast of Norwegian Sea.

The results also confirm that cold-water organisms are generally negatively affected and warm-water organisms are positively affected by climate warming [79].

5. Conclusions

Climate change will significantly affect suitable conditions for the considered species. For species whose range is within the temperate and subtropical zones (*L. gibbosus* and *P. parva*), the conditions in Europe will improve, and for *P. glenii*, whose range is entirely in the temperate zone, they will worsen. For *L. gibbosus* and *P. parva*, there will be a significant expansion of the zones with suitable conditions in the northern and eastern directions; at the same time, there will be a slight improvement in the suitability of conditions for existing populations of *P. parva* and a neutral or slightly negative change for *L. gibbosus*, primarily in southern Europe. The zones with suitable conditions for *P. glenii* will shift to the north, reducing the suitability of the conditions in the central and southern parts of the range while significantly improving them in the northern part. In general, for this species in Europe, the area with suitable conditions tends to decrease. Thus, in Europe, in the short term (the 2050s) and medium term (the 2070s), climate change will have a positive

impact on the habitat conditions for *P. parva* in Europe, and it will have a positive impact in the short term and a moderately positive impact in the medium term for *L. gibbosus* and a negative impact for *P. glenii*.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15112091/s1, Figure S1_1: Occurrences, spatially rarefied per 100 km and used in Maxent models; Figure S1_2: MESS Results of MESS analyses performed to assess whether the HSM accurately predicts the future distribution of suitable habitats; Table S1_1: Pearson's correlation coefficient (absolute values) of bioclimatic factors; Table S1_2: Maxent model options and evaluation metrics; Figure S2_Le1: Prediction of suitable habitats for *Lepomis gibbosus* at the current time; Figure S2_Le2: Prediction of suitable habitats for *Lepomis gibbosus* in the SSP2-4.5 scenario at 2050 (2041–2060); Figure S2_Le3: Prediction of suitable habitats for *Lepomis gibbosus* in the SSP2-4.5 scenario for 2070 (2061–2080); Figure S2_Le4: Prediction of suitable habitats for *Lepomis gibbosus* in the SSP5-8.5 scenario for 2050 (2041–2060); Figure S2_Le5: Prediction of suitable habitats for *Lepomis gibbosus* in the SSP5-8.5 scenario for 2070 (2061–2080); Figure S2_Pe1: Prediction of suitable habitats for *Perccottus glenii* at the present time; Figure S2_Pe2: Prediction of suitable habitats for *Perccottus glenii* in the SSP2-4.5 scenario for 2050 (2041–2060); Figure S2_Pe3: Prediction of suitable habitats for *Perccottus glenii* in the SSP2-4.5 scenario for 2070 (2061–2080); Figure S2_Pe4: Prediction of suitable habitats for *Perccottus glenii* in the SSP5-8.5 scenario for 2050 (2041–2060); Figure S2_Pe5: Prediction of suitable habitats for *Perccottus glenii* in the SSP5-8.5 scenario for 2070 (2061–2080); Figure S2_Ps1: Prediction of suitable habitats for *Pseudorasbora parva* at current time; Figure S2_Ps2: Prediction of suitable habitats for *Pseudorasbora parva* in the SSP2-4.5 scenario for 2050 (2041–2060); Figure S2_Ps3: Prediction of suitable habitats for *Pseudorasbora parva* in the SSP2-4.5 scenario for 2070 (2061–2080); Figure S2_Ps4: Prediction of suitable habitats for *Pseudorasbora parva* in the SSP5-8.5 scenario for 2050 (2041–2060); Figure S2_Ps5: Prediction of suitable habitats for *Pseudorasbora parva* in the SSP5-8.5 scenario for 2070 (2061–2080); Figure S3_1: Relative importance of different predictor variables based on results of jackknife tests in MaxEnt; Figure S3_2: Response of r100b2000 model for *Lepomis gibbosus* to the variation in each predictor when all other predictors were kept at their average values; Figure S3_3: Response of r100b2000 model for *Perccottus glenii*, to the variation in each predictor when all other predictors were kept at their average values; Figure S3_4: Response of r100b2000 model for *Pseudorasbora parva* to the variation in each predictor when all other predictors were kept at their average values.

Funding: This research received no external funding.

Data Availability Statement: Tiff files for the GIS software presenting the predicted probability of environmental suitability are available from Dryad: https://datadryad.org/stash/dataset/doi:10.5061/dryad.b8gtht7hq, accessed on 20 April 2023.

Conflicts of Interest: The author declares no conflict of interest.

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