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Predicting Potential Habitat Changes of Two Invasive Alien Fish Species with Climate Change at a Regional Scale

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Abstract: Developing national-level policies related to climate change induced expansions of invasive species requires predictive modelling at a regional scale level. This study aimed to predict future changes in the habitat distributions of two major invasive alien fish species, *Micropterus salmoides* and *Lepomis macrochirus*, in South Korea. An ensemble system with multiple species distribution models was used for the prediction, and gridded water portion data from the linear-structure information on river channels inputted as habitat characteristics of freshwater ecosystem into the models. Bioclimatic variables at 20-year intervals from 2001 to 2100 were generated from predicted temperature and precipitation data under the representative concentration pathway 4.5 and 8.5 scenarios. The overall distribution probabilities of the potential habitats increased with time in both climate change scenarios, and the potential habitats were predicted to expand to upstream areas. Combined with regional ecological value information, such as biodiversity in freshwater ecosystems, these results can be an important basis for deriving regional priority information for managing alien species in climate change. Additionally, the modelling approach is highly applicable to various national-level policies for ecosystem conservation since it is not greatly restricted by spatial scales.

Keywords: invasive alien species; freshwater ecosystem; climate change impact; species distribution modelling; regional-scale application; habitat expansion

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1. Introduction

Ecological disturbances caused by alien invasive species are a major threat to local ecosystems and native species, and it has been increasingly reported that climate change can be an additional factor accelerating habitat expansion of alien species in some regions [1–4]. Controlling alien species introduction pathways and habitat expansion has been a strong recommendation of the UN Convention on Biological Diversity (CBD) for conserving global biodiversity [4]. There have been several governmental efforts to control habitat expansion of invasive alien species. Decision-making for political actions is generally based on risk assessments of potential threats posed by alien species with regard to reproductive capacity, the possibility of negative impacts on native ecosystems, and biodiversity [5–7]. However, climate change, which may possibly be an additional factor for alien species expansion, is of lower concern.

Largemouth black bass, *Micropterus salmoides* (Lacepède, 1802), and bluegill, *Lepomis macrochirus* (Rafinesque, 1819), are the major invasive alien fish species, designated by the Enforcement Decree of the Ministry of Environment in South Korea. Largemouth black bass is known to have originated in eastern North America and northern Mexico. It mostly inhabits soft riverbeds with aquatic plants, slow water velocity (6–20 m/s), appropriate oxygen concentration (~4 mg/L), temperatures between 11–29 °C for spawning, and slightly alkaline water (5 < pH < 10) [8–10]. The major food sources for this species are microcrustaceans and microworms. Bluegill can be found in states in central North America, such as Virginia, Florida, Texas, and New York, where the river has a narrow channel and complex habitat. These species prefer relatively high temperatures (17 °C < temp. < 21 °C) and low river velocities [8]. These species typically consume zooplankton or microinvertebrates.

In the late 1960s, the Fisheries Agency in South Korea introduced them to expand fish industries in some local communities to expand fish industries in some local communities [11–14]. However, the policy unintentionally caused severe ecological disturbances in freshwater ecosystems due to their nationwide expansions in Korea. Countermeasures by the central and local governments in Korea have restrained the expansions of the invasive species through policy-wise capture and attained fairly successful reductions in their numbers. Currently, the Korean government is continuously monitoring the habitat expansions of the alien species and investigating the human-induced factors that affect their expansion. However, climate change has not been considered a potential environmental factor. Since the species originated from climate zones warmer than those in Korea, the impact of these species expansions due to climate change may need careful inspection.

General approaches for assessing the impact of alien species expansion on climate change include predictions using species distribution models (SDMs). SDMs have been used to predict potential species distributions based on climate change scenarios [15–17]. SDMs are geographical information system (GIS)-based models that can be used to predict potential species habitats using species presence/absence data and environmental information. According to Guillera-Arroita et al. [18], SDMs are applied for various purposes, such as species management, predicting climate change impacts, and landscape management. Several algorithms have been used to predict species distribution, including the general linear model (GLM), general boosted model (GBM), generalized additive model (GAM), artificial neural network (ANN), and random forest (RF). Each of these has its own uncertainty, and ensemble techniques that combine their multiple model outputs are often used to minimize uncertainties [19]. Currently, SDMs are used to predict the distribution of invasive species [20–22].

However, one of the challenges for simulating spatial distributions of fish species on a regional scale is to incorporate the geographical information of their habitats into the models. Since most SDMs use gridded spatial data for environmental information, including climate conditions, data processing from vectorized linear structures of river channels (as in polylines) to gridded scalar data at a lower scale (for example, at 1 km resolution or lower) can cause critical bias. Modelling with lower resolutions is often accompanied by the loss of important habitat information, such as small streams [23–26]. However, climate change studies have generally been limited to models with lower spatial resolutions (several square kilometers at most) due to technical difficulties in valid data production of future climate change at a high scale [27,28].

This study aimed to examine a regional-scale application for SDM simulations of invasive alien fish, largemouth black bass and bluegill, with climate change in Korea. The simulated future spatio-temporal prediction of alien species can help diagnose the impact of climate change on the alien species at a national level in freshwater ecosystems.

2. Materials and Methods

2.1. Study Region and Observations of the Invasive Alien Fish Species

The study region is South Korea whose total area is about 100,000 km^2. South Korea shows a temperate climate condition, annual temperature is about 12.5 °C from −2.0 °C in the coldest month to 26.0 °C in the warmest month, and annual precipitation is about 1200 mm. Due to the nature of the aliens' habitats, South Korea has a slightly cold climate, and thus future warming is likely to provide a more favorable climate condition.

Data largemouth black bass and bluegill were obtained from a survey conducted by the Division of Ecological Safety of the National Institute of Ecology. A total of 380 points were used for the SDMs for bass and 180 for bluegill, which were collected from 2015 to 2018 during the national survey of alien species. The distribution of each species is shown in Figure 1.

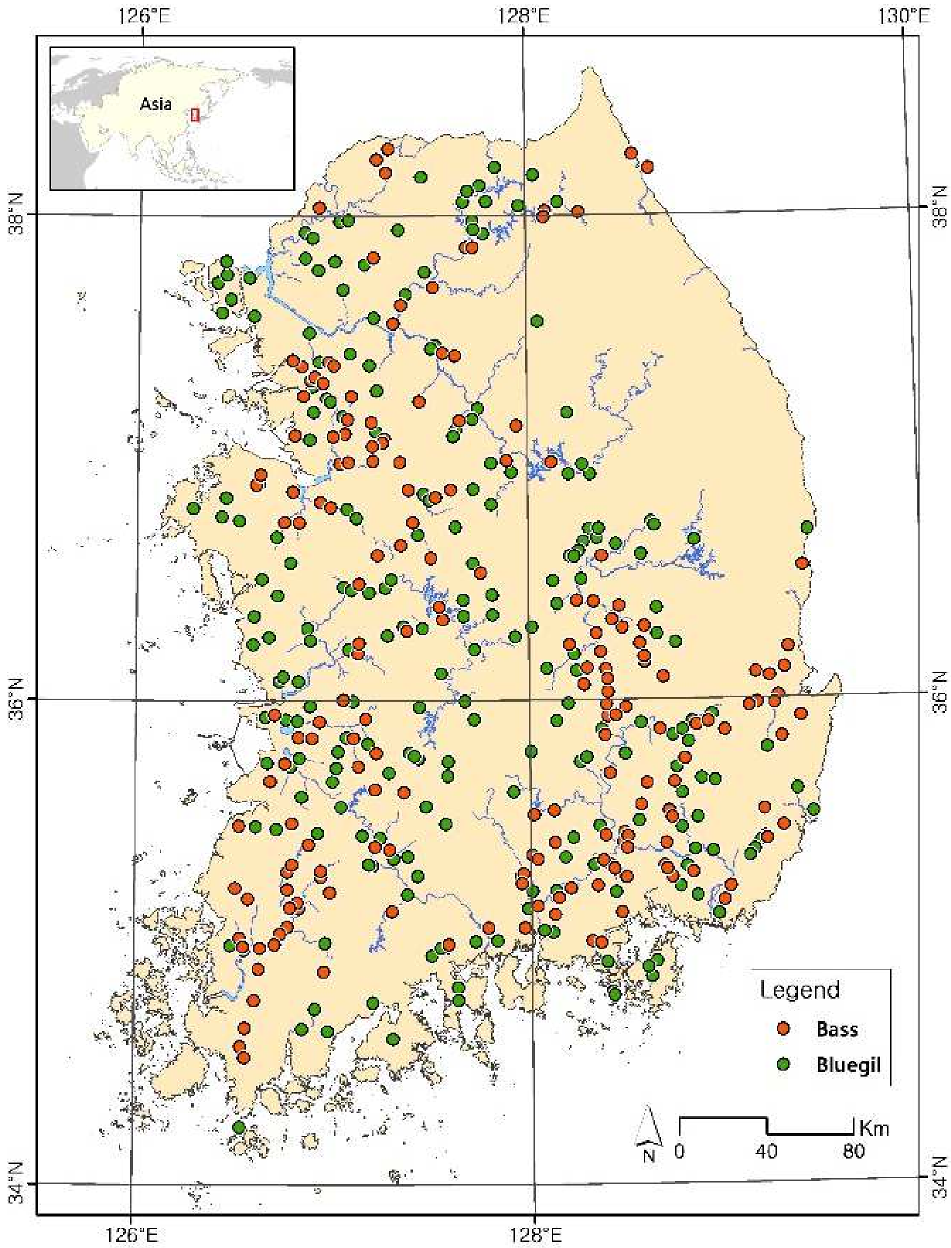

Figure 1. Distribution map of the two invasive alien species, largemouth black bass (red dots) and bluegill (green dots), with the study domain (the yellow shaded area), Korean Peninsula. Blue lines are the major river channels in the domain.

2.2. Species Distribution Models

An ensemble approach with multi-SDMs in the BIOMOD system [29] was used to improve the accuracy of using a single model. In BIOMOD, 10 different mathematical prediction algorithms are available for ensemble simulations: GLM, GBM, GAM, classification tree analysis, ANN, surface range envelop, flexible discriminant analysis, RF, multivariate adaptive regression splines, and MaxEnt. The simulation performance of each model is validated using 20% of randomly selected species input data. Then, the final ensemble model outputs are obtained by a composite of weighted SDMs based on the diagnostic index indicating the modelling performance and true skill statistics [30,31].

2.3. Input Data for SDMs

For the current climate conditions in the SDMs, 19 bioclimatic variables (BIOCLIMs) were generated from WorldClim (accessed on 2 March 2019. BIOCLIMs were processed to have a 1 km spatial resolution based on global climate observations for approximately 50 years since 2000 [32]. The final variable selections as the model inputs were carried out through covariance analyses among all BIOCLIMs for South Korea. Once a high correlation between two selected variables (0.7 or higher in Pearson's correlation coefficient in this study) was shown, one of them was excluded from the list of inputs [33–35]. The final BIOCLIM inputs selected for this study, three temperature-related and three precipitation-related inputs, are shown in Table 1.

Table 1. Selected BIOCLIMs for model inputs.

Name	Description	Name	Description
BIO1	Annual mean temperature	BIO12	Annual precipitation
BIO2	Mean diurnal range	BIO13	Precipitation in the wettest month
BIO3	Isothermality	BIO14	Precipitation in the driest month

For future climate conditions, predicted temperatures and precipitation based on the two climate change scenarios, representative concentration pathway (RCP) 4.5 and 8.5, as defined by the Intergovernmental Panel on Climate Change (IPCC) [36], were obtained from the Korean Meteorological Administration (KMA). The KMA data were statistically downscaled (1 km resolution) from a global climate model output (25 km resolution) with geomorphological characteristics at a higher resolution [37,38]. To examine temporal variations in species distributions, the data were further processed to generate 20-year-averaged monthly climate data for four different time periods: 2021–2040, 2041–2060, 2061–2080, and 2081–2100.

According to the KMA climate change predictions, temperature in Korea is expected to increase at the rate of approximately 0.28 and 0.6 °C per 10 years until 2100 under RCP 4.5 and 8.5 scenarios, respectively. More rainfall is predicted in both climate change scenarios until the end of the 21st century, while the spatial variabilities in rainfall regimes are very different between the two scenarios; the standard deviations are 1.2 and 1.7 mm/year on average for the RCP 4.5 and 8.5 scenarios, respectively (Figure 2). A total of 19 BIOCLIMs were generated using the same method as the WorldClim datasets, and only six BIOCLIMs, as listed in Table 1, were applied to the model simulation.

As an essential habitat characteristic of freshwater ecosystems, water portion data were applied to the model as a geographical input. Those were made with the intention of reflecting the water amount for the rasterized model structure. To reflect the river channel characteristics in these low spatial analyses, Korea's national land use land cover data gridded into 5 m resolution, which is provided by the Korean Ministry of Environment (via egis.me.go.kr, accessed on 7 April 2022), were utilized to extract water body information. Then, the area percentage of the water body was inscribed into each 1 km^2 grid to avoid habitat information loss for freshwater ecosystems (Figure 3).

Gridded slope data generated from the digital elevation model (DEM) of Korea were used as an additional geographical input. These data were considered to indirectly represent the water streaming velocity. The DEM was excluded as a model input due to its high covariance with the average temperature.

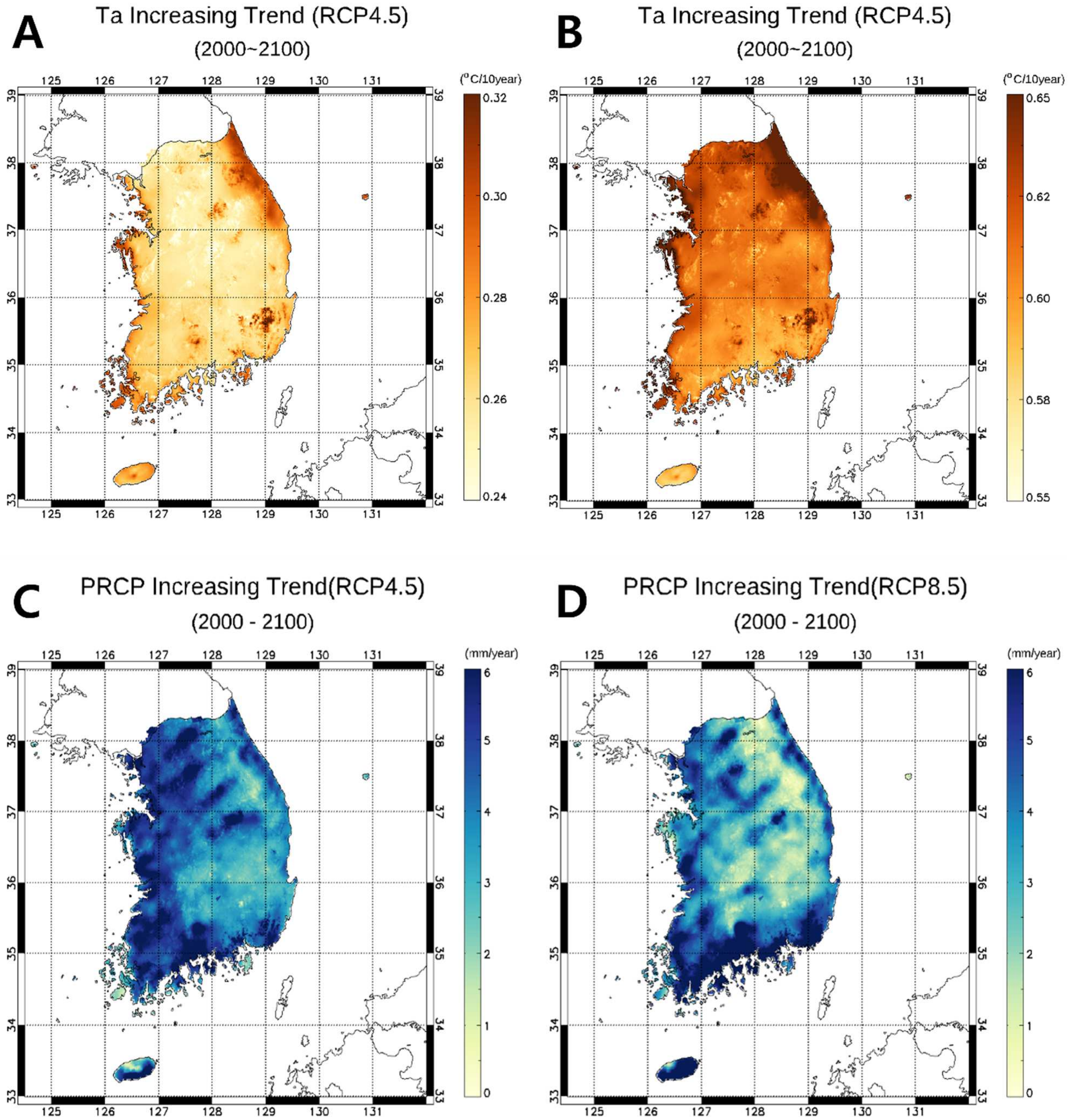

Figure 2. Temperature (Ta) (**A**,**B**) and precipitation (PRCP) (**C**,**D**) increasing trends for one hundred years (2000–2100) predicted for South Korea, under RCP4.5 (**C**) and RCP4.5 (**D**) scenarios. Note the differences of color bars' scale of temperature increasing speeds.

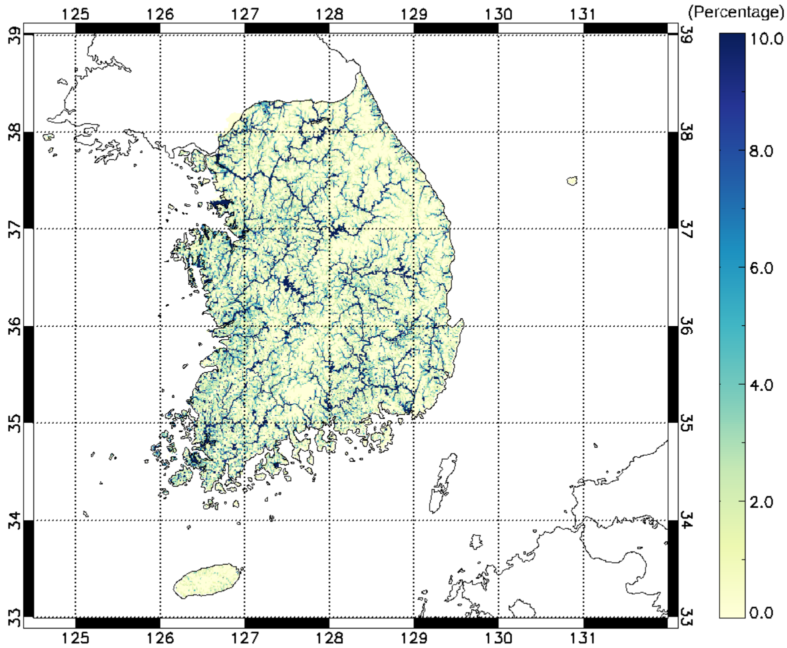

Figure 3. National water portion map of Korea gridded in a 1 × 1 km resolution.

3. Results

3.1. Simulated Current Status of the Habitat Distribution of the Invasive Alien Species

The indices for modelling performance, true skills statistics (TSS), and receiver operating characteristic (ROC) were relatively high: 0.79 for TSS and 0.97 for ROC. According to the modelling contributions of the input variables, the water portion map showed the highest contribution to modelling for both alien fish species, 93.6% for largemouth black bass and 83.8% for bluegill (Table 2). This indicates that proper habitat information is crucial for modelling these species. In addition, these results show that the water portion information in this study may make it easier to apply SDMs to regional-scale modellings regardless of spatial resolution, especially for freshwater ecosystems. The next most important variable was BIO1 for both species, implying that it is a climate-related environmental descriptor for freshwater ecosystems. In fact, BIO1, mean atmospheric temperature, is not a direct habitat characteristic, but due to the general relationship between atmospheric and freshwater temperatures, it is indicated that the future increase in atmospheric temperature will affect the species habitat distribution in the SDMs. In contrast, precipitation-related BIOCLIMs and slope information had relatively low contributions. Information of the model predictions to input variables were provided in Appendix A.

Table 2. Percentages of modelling contribution and permutation importance for each input variable.

Variables	Largemouth Black Bass		Bluegill	
	Contribution (%)	**Importance (%)**	**Contribution (%)**	**Importance (%)**
BIO1	2.7	3.3	10.2	10.3
BIO2	0.7	0.7	2.3	4.4
BIO3	0.4	1.1	0.3	2
BIO12	0.2	0.3	0.6	1.1
BIO13	0.5	0.8	1.2	1.1
BIO14	1.5	0.8	0.9	0.7
Slope	0.4	0.6	0.7	0.3
Water Portion	93.6	92.3	83.8	80.1

Figure 4 shows the potential habitat distribution of largemouth black bass and bluegill, simulated from BIOMOD under current climate conditions (2001–2020). The results showed a highly concentrated distribution of habitats, mainly on major river channels. Both species were simulated to be concentrated in the Nakdong and Yeong-san River basin. The total areas showing high probability (70% or higher) were 9369 km^2 for largemouth black bass and 7649 km^2 for bluegill.

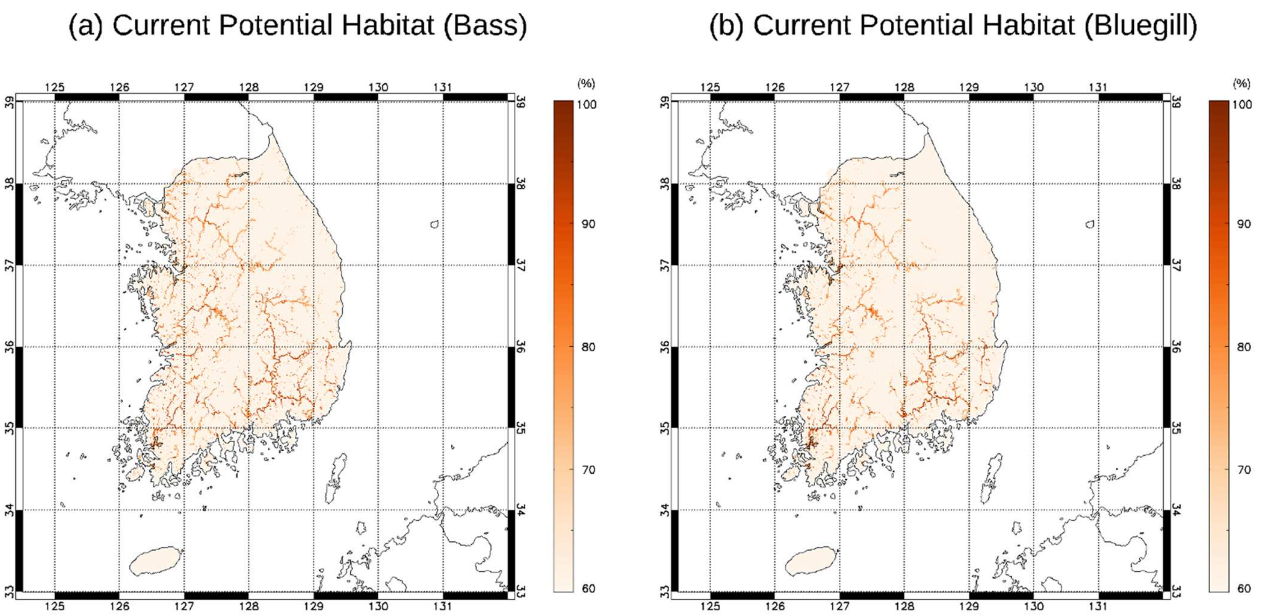

Figure 4. Simulated current potential habitat of largemouth black bass (**a**) and bluegill (**b**). The simulated inhabitable probability in percentage is color-coded in each grid.

3.2. Future Simulations of Habitat Distributions of the Invasive Alien Species

Future simulations showed that habitats with a high probability would increase by 2100 (Figure 5). Based on the current total areas of 70% or higher probabilities, the area percentages of largemouth black bass were predicted to expand up to approximately 130% and 125% by 2100 under RCP 4.5 and 8.5 scenarios, respectively. Similarly, those of bluegill were predicted to expand up to 160% and 170% by 2100 under RCP 4.5 and 8.5 scenarios, respectively.

Figure 6 shows the relationship between future potential habitats and water bodies. The high habitat probability (70% or higher) under the current status was observed in regions (or grids) with 12% or higher for largemouth black bass, and 15% or higher for bluegill water bodies. The peak habitat probability for largemouth black bass occurred at approximately 25% of the water portion, while the maximum habitat probability of bluegill was saturated at approximately 30% of the water portion and then started to fluctuate at approximately 80% of the probability. Although the habitat distribution patterns differed between the species, this indicates that the water portion is the most influential factor in describing the habitat characteristics of both species in the models. Interestingly, future simulations showed an increase in habitat probabilities for almost all magnitudes of river channels, implying a strong impact of climate change on the expansion of alien fish species. In addition, high distribution probabilities appeared in the lower water part area over time, implying that climate change may cause alien fish to expand toward smaller magnitudes of river channels.

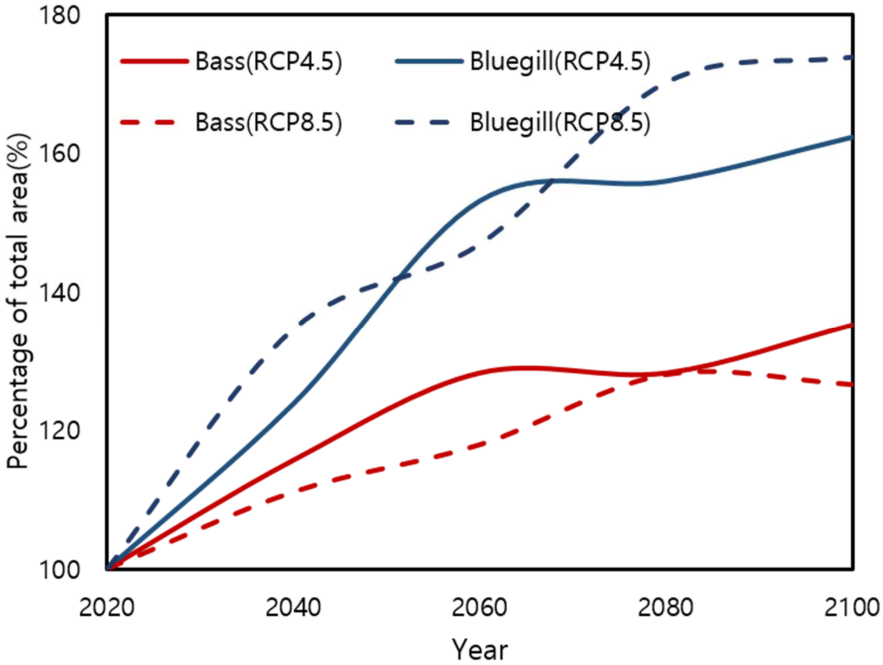

Figure 5. Future changes in simulated habitat probability (70% or higher) for largemouth black bass (red solid and dashed lines for RCP 4.5 and 8.5) and bluegill (blue solid and dashed lines for RCP 4.5 and 8.5) in percentage based on the current total areas of high habitat probability.

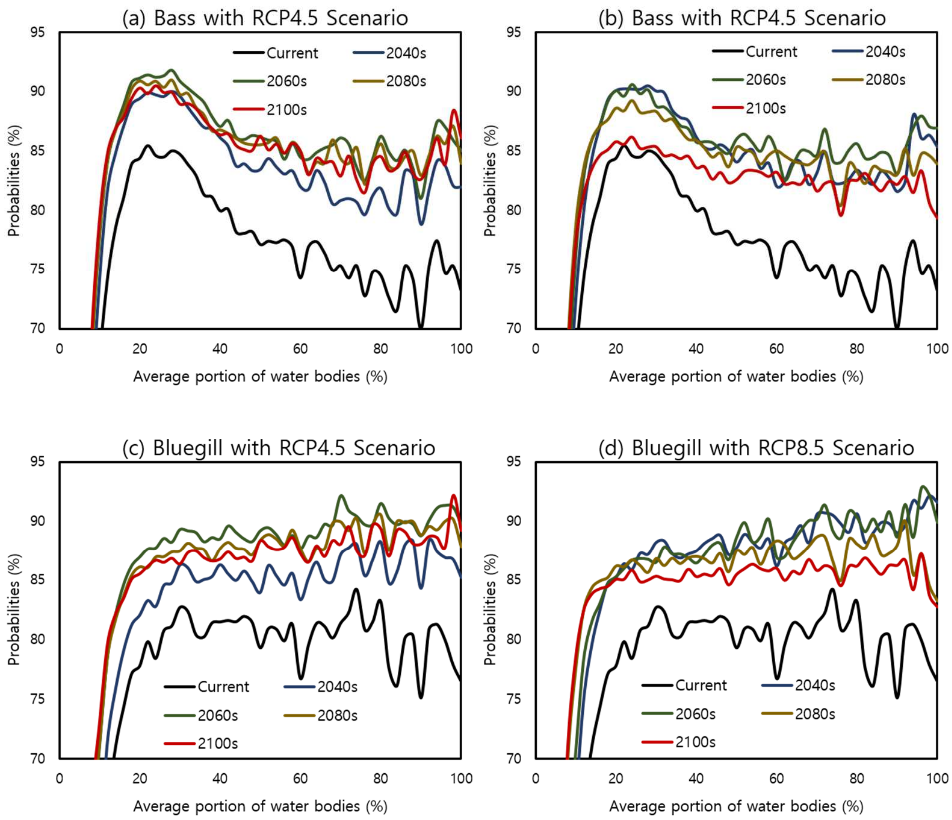

Figure 6. The portions of water bodies versus probabilities of potential habitats for largemouth black bass and bluegill under the two climate change scenarios. Each colored line indicates a different time period: Black, blue, green, brown, and red for current, 2040 s, 2060 s, 2080 s, and 2100 s, respectively.

4. Discussion and Conclusions

This study conducted modelling experiments using an ensemble system with multiple SDMs to diagnose the effects of climate change on the possibility of habitat expansion of major invasive alien fish species in South Korea. In particular, for the application of SDMs to fish on a regional scale (applied at the national level for South Korea in this study), water portion data were designed for model input as a habitat characteristic of freshwater ecosystems and played a very decisive role in describing the highly realistic patterns of fish distribution within the model. This approach is expected to be very useful in SDM applications (only for those in rasterized model structures), regardless of spatial resolution to a certain extent. This can possibly be useful in application to larger areas with lower spatial resolutions. It can also be extensively applied not only to alien species but to all species in freshwater ecosystems.

The impact of future climate change on the distribution of invasive alien fish species is clear. Areas with a habitat distribution probability of >70% clearly showed a tendency to expand over time. However, the degree of impact of climate change was predicted to be greater for bluegill than for largemouth black bass. A major uncertainty during the process of examining the impact of climate change using SDMs was the lack of consideration of the possible route between watersheds for species migration. Due to the nature of freshwater ecosystems, habitat connectivity (or hydrological connectivity between watersheds within river channels) should be considered as an influential factor in describing species migration. Another considerable factor in terms of species movements might be the obstructive effects of artificial structures in river streams, such as dams. It is necessary to apply the data on paths and mechanisms related to species movement to SDMs to reduce these modelling uncertainties. Nevertheless, this study showed that climate change will cause species expansion toward upstream areas within hydrologically bonded watersheds.

The expansions of these alien fish into upstream areas are likely to be the effect of the temperature rise; temperature showed the second most contribution for model predictions. Warm water fish, such as the alien species in this study, has been studied to expand to higher locations with temperature increase [39–41]. In this upstream area, species abundance is generally lower, but rare and insectivorous species are largely distributed [42]. Cold water species in these upstream areas with higher altitudes have been reported to be more vulnerable to warming environments [43–45], and thus expansions of alien species are likely to exacerbate the species vulnerabilities significantly more [46,47]. Their ecological disturbing behaviors have been mainly reported since their introduction in Korea: Lowering the species diversity and degrading the sustainability of native fish species [48–50].

The information regarding the expansion of invasive alien fish due to climate change in this study can help establish strategic countermeasures, even by simple combination with local ecological information, such as biodiversity. This approach can help derive priority area information for ecosystem conservation. For example, among habitats with high biodiversity, those with high expansion possibilities for alien species can be selected as higher priority for conservation. Areas inhabited by endangered species or those vulnerable to climate change can provide additional information for priority selection. Furthermore, it will help derive a more specific regional methodology for reducing alien invasion impact by adding disturbance characteristics of alien species, such as disturbances, feeding habits, and competing species.

Author Contributions: Conceptualization, S.H.; methodology, I.J., K.L., and D.K.; data curation, S.K.; formal analysis, S.H. and K.L.; writing—original draft preparation, S.H. and I.J.; writing—review and editing, S.H. and K.L.; and visualization, S.H. and H.S.P. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: BIOCLIMs can be found at http://worldclim.org (assessed on 2 March 2019) and future predicted climate data for South Korea at http://climate.go.kr (accessed on 21 June 2019). The species observation data and the current and future simulations of the species distributions are available on request to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The following plots show information the impact of each covariate on the species presence probability.

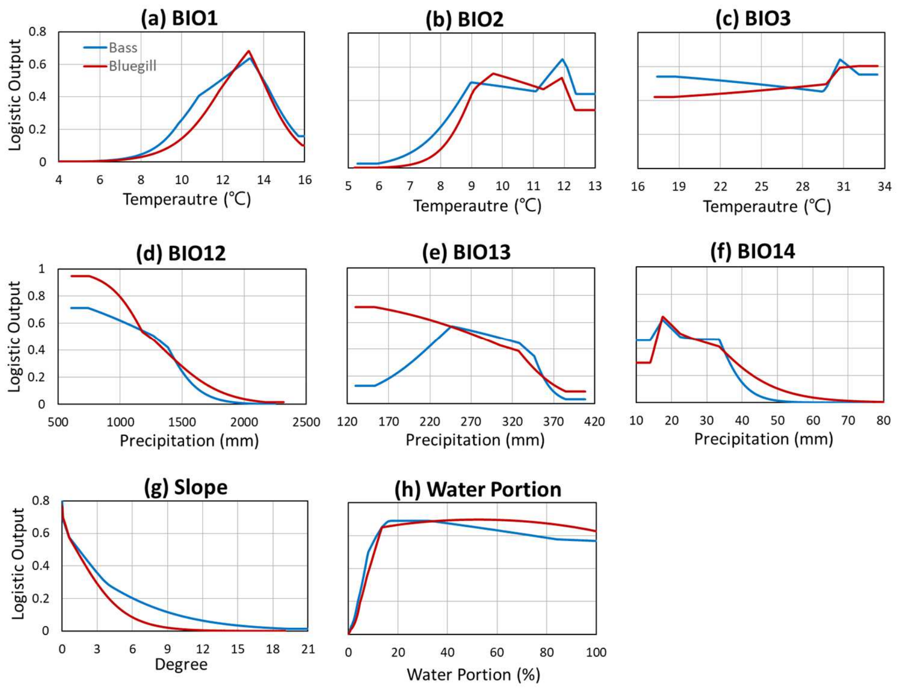

Figure A1. Response curves of the model predictions to the input variables when only the corresponding variables are used.

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