Species Distribution Modeling to Predict Invasion Risk of Nutria (*Myocastor coypus*) in Japan

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ABSTRACT

Nutria, a large aquatic rodent native to South America, is categorized as an invasive species in Japan and regulated to prevent harm to the economy and native ecosystems. Despite the regulation efforts, the population size and distribution range of nutria is still expanding in Japan due to their rapid reproductive cycle. Although the impact of nutria in increasing, few studies have been conducted on them in Japan. In this study, I will investigated the areas with potential risk of nutria invasion and climatic characteristics that are associated with the nutria distribution in Japan by using Maxent Species Distribution Modeling. I produced two prediction models using both Japanese climatic and occurrence data and American climatic and occurrence data. As a result, I found that using Japanese data produced a better prediction of nutria's potential distribution. I also found that Kanto region and northern Kyushu region are at risk for potential nutria invasion. The pattern of correlation between nutria presence and climatic variables were different between nutria in Japan and that in the U.S.

KEYWORDS

invasive species, potential distribution, ecological niche modeling, spatial scale, climate

INTRODUCTION

Japan's unique island ecosystem makes it susceptible to the impacts of invasive species (Goka 2010). Because of this susceptibility, many studies have been conducted to document the impacts of and improve the knowledge about non-native and invasive species in Japan (Hamaguchi et al. 2017 & Takahara et al 2017 & Goka 2010). Invasive species have been reported in both terrestrial and aquatic ecosystems and their presence and distribution are influenced by climate, landscape, and vegetation (Takano et al. 2017 & Saito et al. 2016). Despite the recent attention to this area of research, the focus of these studies has been on the insects, microorganisms, and plants. There are far fewer studies for mammals. Therefore, it is important to better understand the impacts of mammalian invasive species in Japan.

Nutria (*Myocastor coypus*), a large aquatic rodent native to South America, is one of the invasive mammalian species in Japan. Nutria were introduced to Japan deliberately for the fur trade in 1900s and became quickly established in the wild over the next fifty years. By the early 1960s, the negative impact of nutria on agricultural crops was already apparent (Iori et al. 2013). In the present-day Japanese society, environmentalists and those who are impacted by the nutria invasion are concerned about nutria's harmful impacts on the native landscapes, native species, and agricultural crops (NIES). Due to this impact, nutria are categorized as an invasive alien species and regulated under the Invasive Alien Species Act (Reade et al. 2014). This act defines invasive alien species as the non-native species that cause or might cause environmental, economical, or human-related damage (Goka 2010). Even though more than 50,000 nutria were culled under regulation during last 10 years, the range of nutria is still expanding leading to more than one million dollars of agricultural crop damage each year. This agricultural damage is especially a problem in western Japan (Iori et al. 2013). Since the current regulation is insufficient and the nutria's range is still expanding, other areas, such as eastern Japan, might be affected by nutria invasion in the near future.

Despite the possibility of the expanding impact of nutria, a limited number of studies have been conducted on this harmful species. The past studies of nutria in Japan were conducted largely on its biology, ecology, current impact on agricultural crops, and historical change in the distribution. These studies found that nutria in Japan become sexually mature at 4-6 months of age and reproduce at a rate of about 8.6 offspring per female per year, without seasonal fluctuations, until they die at age of 4-5 years. They live in wide variety of waterfront environment, including rivers, small reservoirs, brackish waters, and urban concrete water-channels. Also, they have a wide dietary range, including water plants, benthic unionid bivalves, and agricultural crops (Kobayashi and Kawamura 2012 & Kobayashi and Kawamura 2013 & Iori et al. 2013 & Mori 2010). However, little to no information is available for nutria's potential impact and distribution areas in Japan. To properly regulate and control nutria and protect native ecosystem and economic interests, it is crucial to investigate the potential regions at the higher risk for nutria invasion.

The main goal of this study is to determine the areas with higher potential vulnerability to the nutria invasion in Japan. To do this, I will 1) predict the potential distribution range of nutria in Japan through species distribution modeling, 2) test the model with nutria's actual distribution in Japan, and then 3) define the climatic characteristics of nutria's habitat. I hypothesize that nutria's distribution in Japan is similar to the model produced based on the environmental characteristics and nutria's distribution in the world, but there are also some areas that are not yet invaded by nutria and are at risk of nutria invasion in the near future.

METHODS

Study Sites

I collected the data in two countries, the United States and Japan. The U.S. and Japan are located at similar latitudes, 38 °N for the U.S. and 36°N for Japan, and both countries vary in their climatic characteristics. The majority of the U.S. has a temperate climate, with smaller regions with tropical, arctic, semiarid, and arid climates. Japan's climate varies from North to South. The South has a relatively tropical climate compared to the cooler temperate climate of the North (Central Intelligence Agency…). Both the U.S. and Japan experienced the introduction of nutria in the 1900s largely due to the fur trade, and the environments of the both countries differ from the native environment for the nutria. Nutria were established in the wild and have had ongoing impacts on the environment and human society in both countries since the introduction (Carter and Leonard 2002).

Data Source Databases

To determine the nutria's current distribution of nutria in the U.S. and Japan, I collected geo-referenced data from two online databases - the Global Biodiversity Information Facility (GBIF) and Biodiversity Center of Japan (BCJ). The GBIF database included nutria occurrence data from many different sources, including museum data and citizen science platforms. These sources included USGS Nonindigenous Aquatic Species database, LSUMZ Mammals Collection, iNaturalist Research-grade Observations, NMNH Extant Specimen Records, MSB Mammal Collection (Arctos), TTU Mammals Collection, Angelo State Natural History Collections (ASNHC) - Mammalogy Collection, Vertebrate Zoology Division - Mammalogy, Yale Peabody Museum, ISM Mammalogy Collection, and CUMV Mammal Collection (Arctos). The GIBF occurrence data for nutria was compiled from observational data, preserved specimen data, and fossil specimen data all with the latitude-longitude coordinates. I also collected the occurrence data from Biodiversity Center of Japan (BCJ). BCJ is the Japanese government website that provides the GIS data collected by their biodiversity survey. The BCJ occurrence data were observational data.

Data Selection

In the GBIF database, I collected 1030 occurrence data for the U.S. and 5 data in Japan. For the BCJ, I collected nutria occurrence data from 4^{th} and 5^{th} surveys, which were conducted between 1988 and 1993 and between 1993 and 1999 respectively. I chose 4^{th} and 5^{th} surveys among their 5 surveys because these were the only surveys included nutria data. I collected 123 data from 5th survey and 231 data from 4^{th} survey. The coordinates data from the BCJ were in the form of Japanese grid cell system, which divides the geographical area into grid square cells and assign numbers to each cell. I converted it into the latitude and longitude coordinate reference system by using the online website, GIS-tool.com.

Climate Data

To include the possible variables that could influence the distribution pattern of nutria in the species distribution modeling, I collected climatic variables. I collected 19 climatic variables with 30 seconds resolution in raster format from the WorldClim database. These variables were Annual Mean Temperature, Mean Diurnal Range (Mean of monthly (max temp - min temp)), sothermality, Temperature Seasonality (standard deviation *100), Max Temperature of Warmest Month, Min Temperature of Coldest Month, Temperature Annual Range, Mean Temperature of Wettest Quarter, Mean Temperature of Driest Quarter, Mean Temperature of Warmest Quarter, Mean Temperature of Coldest Quarter, Annual Precipitation, Precipitation of Wettest Month, Precipitation of Driest Month, Precipitation Seasonality (Coefficient of Variation), Precipitation of Wettest Quarter, Precipitation of Driest Quarter, Precipitation of Warmest Quarter, and Precipitation of Coldest Quarter (WorldClim).

Data Analysis

In order to predict the potential distribution of nutria in Japan, I used Maximum Entropy Species Distribution Modeling (Maxent SDM) (Steven et al.). Maxent can predict the distribution of a species by using the occurrence and environmental data. As a preparation of my data for running Maxent model, I used R and ArcMap (R & ESRI). I firstly cropped the 19 bioclimatic data to my study sites, the U.S. and Japan in R. Then, I converted my raster data into ASCII data by using the "Raster to ASCII" tool in ArcMap. After these preparations, I ran Maxent SDM twice. I used Japanese occurrence and climatic data as my inputs for the first run and used American occurrence and climatic data as my inputs to run the prediction on Japan.

To test my models, I mapped current nutria distribution in Japan on the resulting prediction models. I imported the models and Japanese nutria occurrence data into ArcMap to compare each model to the actual distribution of nutria and determine if the models appropriately predicted the nutria distribution in Japan. I also used the Area Under the Receiver Operating Characteristic Curve (AUC) from the Maxent output to rate how good the model performances were. To identify the areas with higher potential risk of nutria invasion in Japan, I used the model with higher AUC value and with higher overlap with actual nutria distribution. I compared the potential distribution of the model and actual distribution of nutria. I determined the areas where had the high probability of nutria presence and were not currently occupied by nutria.

In order to identify the environmental variables that are correlated with nutria distribution, I used Maxent outputs and Principle Component Analysis (PCA). PCA is a statistical method to analyze the correlation between variables and to determine which of these variables best explains the variance of the data (Abdi 2010). For PCA, I firstly imported the environmental layers in R and then extracted the values of the layers at the points where nutria presents. I extracted points for the U.S. occurrence data and Japanese occurrence data separately. Then, I performed PCA with the extracted climatic raster data.

RESULTS

Data Collection

I found that nutria in the U.S. and Japan were widely distributed across each country with areas of higher concentration. My data consisted of 1,030 data points in the U.S. (Fig 1) and 359 data points in Japan (Fig 2). In the U.S., nutria were distributed across the mainland of the country, but they were more concentrated especially in the southeastern and northwestern regions of the lower 48 states. In Japan, nutria were mainly distributed in western region of mainland, but they also were present in eastern and northeastern parts of the mainland. I also found some data points in Shikoku-island, which were the only non-mainland site with nutria presence.

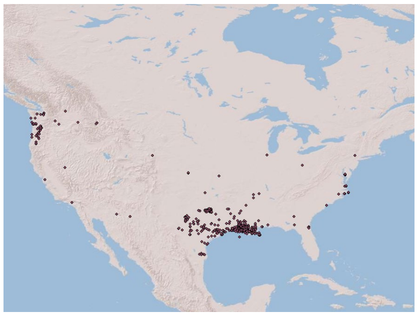

Figure 1: Nutria's Occurrence Data in the U.S.. Points represent occurrence points from the GBIF database. Nutria are concentrated in the southeastern and northwestern regions of the contiguous U.S..

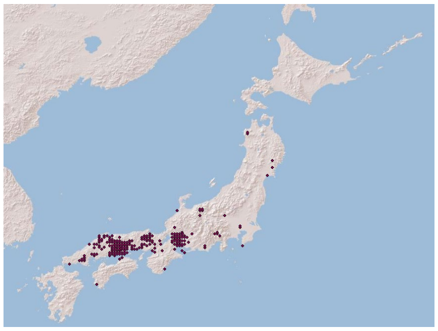

Figure 2: Nutria's Occurrence Data in Japan. Points represent occurrence points collected from GBIF and 4th and 5th surveys of BCJ. The nutria is concentrated on the western region of mainland in Japan.

Predicting the Nutria's Potential Distribution

By performing Maxent SDM, I found that the model produced by using Japanese data (Fig. 3) and the model produced by using U.S. data (Fig. 4) resulted in the very different predictions of potential nutria distribution in Japan. By using Japanese data, the model predicted that the western regions and Kanto regions of the mainland in Japan had higher probabilities of nutria presence while the Hokkaido region and southern Kyushu region were not suitable for nutria presence. The model with U.S. data predicted that the areas along the shoreline were highly suitable for nutria. The model with U.S. data also predicted that small islands on the southern regions of Japan are highly suitable nutria while the northern parts of Japan were not suitable.

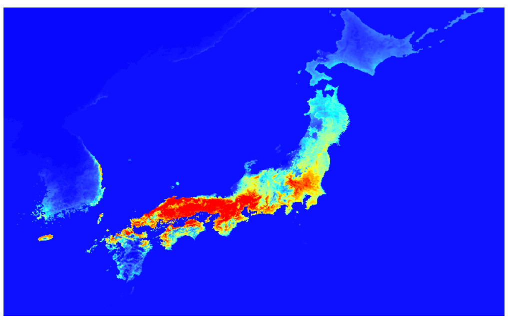

Figure 3: Potential Distribution of Nutria in Japan Predicted by Using Japanese Occurrence and Climatic Data. The areas with higher suitability for nutria are in the western mainland and Kanto area.

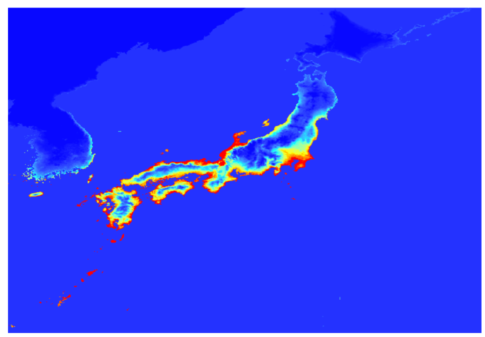

Figure 4: Potential Distribution of Nutria in Japan Predicted by Using U.S. Occurrence and Climatic Data. The areas along the shoreline were predicted to have higher suitability for nutria. However, the northern regions were not suitable for nutria presence.

Testing the Model

By comparing the potential distribution of nutria to their current distribution, I found that the model produced by using Japanese data (Fig. 5) was a better model than the model produced by using the U.S. data (Fig. 6). For the model with Japanese data, I found that the potential distribution and current distribution of nutria were highly overlapping. Most of the current distribution of nutria was in the areas where the model predicted to have the highest probability of nutria presence. For the model with U.S. data, I found that the current nutria distribution was mostly in the areas where the model predicted to have a low probability of nutria presence. The value of AUC for the model with Japanese data was 0.961 and that for the model with U.S. data was 0.919. Since the model with Japanese data had more overlapped areas between predicted distribution and actual distribution and had higher AUC value, I determined that the model with Japanese data produced the best prediction and used the Japanese model to identify the areas with higher potential risk of further nutria invasion in Japan.

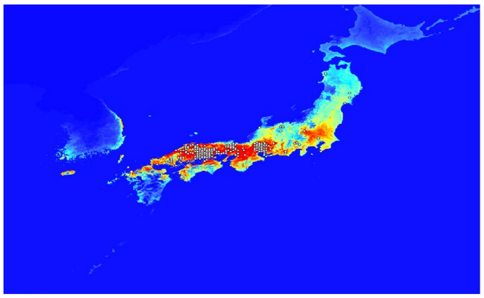

Figure 5: Overlap of Potential Distribution and Actual Distribution for the Model with Japanese Data. Most of the current nutria distribution were in the areas where the model predicted to have high probability of nutria presence, and the predicted distribution was highly overlapped with the actual distribution of nutria in Japan.

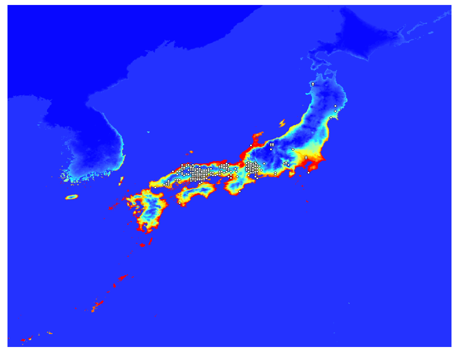

Figure 6: Overlap of Potential Distribution and Actual Distribution of Nutria for the Modal with U.S. Data. The actual distribution of nutria in Japan overlapped with the predicted distribution with small scale. The majority of current distribution were in the areas where the model predicted to have low probability of nutria presence.

Areas with Higher Invasion Risk

By comparing the potential and actual distribution of nutria of the model produced by using Japanese data, I found that current distribution of nutria can expand towards both eastern and western sides. While the current distribution and potential distribution of nutria in Japan were similar to each other, there were some areas with high probability of nutria presence that were not yet occupied by nutria (Fig. 5). These areas included Kanto region and northern Kyushu region. The northeastern and western parts of Sikoku island also had higher risk of nutria invasion. These regions have the higher risk of nutria invasion if nutria expand their distribution range.

Environmental Characteristics

By running Principle Component Analysis (PCA) on the climatic data, I found that the pattern of correlation between nutria presence and climatic characteristics was different between

Japan and the U.S. For the PCA with Japanese data, I found that the first three components explained 85% of the entire data's variance. Almost all of the 19 climatic variables contributed to these three components (Fig. 7). For PCA with U.S. data, I found that the first three components explained 90% of the data's variance and that most of the climatic variables contributed to these three components (Fig. 8). By comparing the results of these two PCA, I found that the climatic preference of nutria in Japan was different from the preference of nutria in the U.S..

Based on the "Analysis of variable contributions" from Maxent outputs, I found that the environmental variables that were associated with the nutria's potential distribution were different between Japan and the U.S.. For the model produced by Japanese data, Temperature Seasonality, Annual Mean Temperature, and Max Temperature of Warmest Month were contributed the most to the model prediction, which accounted for 62.5% of the variance. For the model produced by the U.S. data, I found that Annual Mean Temperature, Mean Diurnal Range, and Precipitation of Driest Quarter contributed the most to the prediction model, which accounted for 69.6% of the variance.

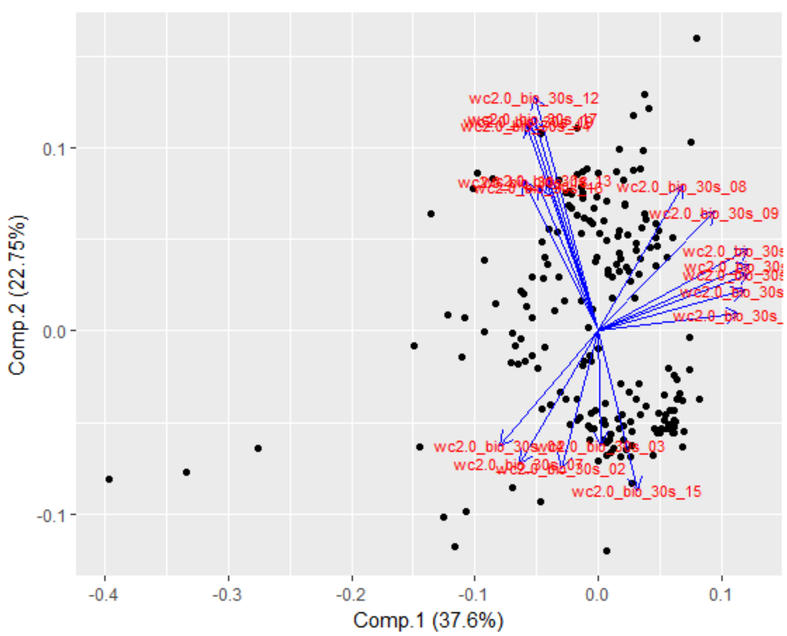

Figure 7: Results of PCA for Climatic Data Extracted by Using the Japanese Nutria Occurrence Data.

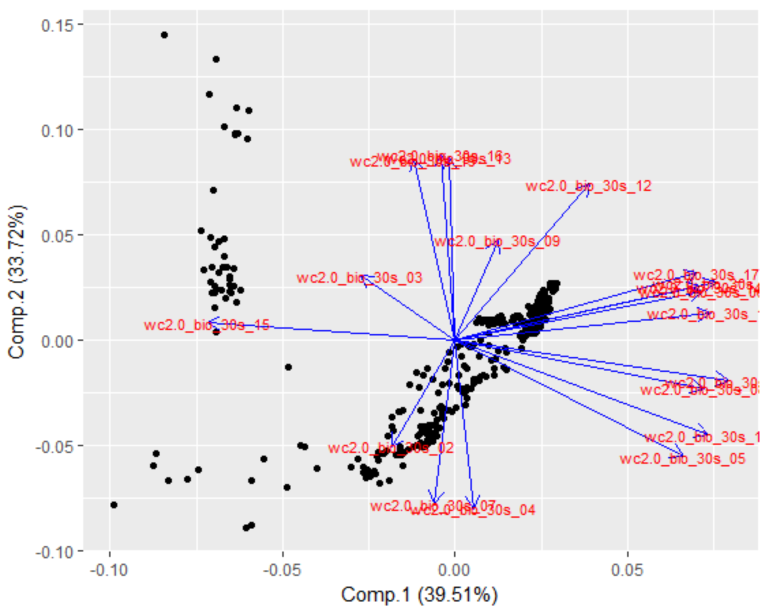

Figure 8: Results of PCA for Climatic Data Extracted by Using the U.S. Nutria Occurrence Data.

DISCUSSION

My study revealed that Kanto and northern Kyushu regions in Japan had higher risk of nutria invasion based on the highly suitable regions that don't currently have nutria. By comparing the prediction models produced by using data from different countries, I found that performing SDM across space can affect the modeling quality. The findings of my study can be used to improve the knowledge about the invasive species distribution pattern and to prevent the further impact of invasive species in Japan.

Potential Distribution Range and Climatic Characteristics

I found that using Japanese and U.S. data produced very different prediction for nutria's potential distribution range in Japan, which suggested that predicting the potential distribution of species by using the occurrence and environmental data from different regions could affect the quality of the prediction model. Maxent SDM with Japanese data predicted that the wide range of western mainland would be suitable for nutria while using the U.S. data predicted that the areas along the shoreline, instead of inland areas, would be more suitable. Comparison between the predictions and actual nutria distribution in Japan revealed that the model with Japanese data produced better prediction. Since performing SDM using Japanese data produced the better model for the potential distribution of nutria in Japan than using U.S. data, it indicates that performing Maxent SDM across different regions can reduce the prediction quality compared to the SDM within a region.

For the invasive SDM, most of the previous studies have predicted the distribution of invasive species in a region by using the environmental and occurrence data from the same region. This was probably because performing SDM within a region is much simpler and easier than performing SDM across different regions. Another reason might be the differences between environmental preferences of invasive species between different regions caused by the local adaptations of invasive species to the novel environment. Invasive species tend to show the adaptive evolution within 20 or less generations, which allows them occupy different habitat types from the habitat type they occupy in their native range. (Oduor et al. 2016 & Prentis et al. 2008). My Analysis of Variable Contributions results from Maxent and results of PCA on 19 climatic variables supported the effects of local adaptations on the model performance by showing the differences in the environmental variables correlated to the nutria presence between Japan and the U.S.. My study revealed that predicting the potential distribution of invasive species can be affected by the differences in the species' environmental preference between different regions.

My study helped to improve the knowledge about the potential suitable areas for nutria presence in Japan because there were no previous studies that investigated the potential distribution of nutria in Japan. Knowing the potential distribution of invasive species is essential to appropriately managing them and reducing their impact. This is because knowledge about the potential distribution helps us plan how to prevent the further invasion. Preventing the further invasion is the primary step to eradicate the invasive species because the eradication efforts, such as trapping or hunting, to manage the population of invasive species are not effective unless we prevent the further invasion (Carter and Leonard 2002). By revealing the potential distribution of nutria in Japan, this study would be helpful for the future management of nutria in Japan.

Areas with Risk of Nutria Invasion

Based on the gap between potential distribution and actual distribution, I found that Kanto and northern Kyushu regions in Japan had higher potential risk of nutria invasion, and this finding suggests that nutria's population and distribution management should focus on these areas to effectively prevent the impact of invasive nutria in Japan. Kanto and northern Kyushu regions have higher risk of invasion because they have have high climatic suitability. The current distribution of nutria in Japan was all within the areas with higher potential probability of nutria presence. This indicates that my distribution model successfully predicted the potential distribution of nutria in Japan.

The previous studies found that invasive species tend to expand their habitat greatly and rapidly in their introduced habitat because of the absence of competing species and the abundance of predators. A previous study compared the otters' potential distribution of Eurasian otters in Spain in 2003 to the actual distribution of the otters in 2008 and found that the otter expanded their habitat range to occupy almost all the available suitable environment predicted by the model in 2003 (Areias-Guerreiro and Barbosa. 2016). The finding of previous study indicates that the potential nutria's habitats in Japan that are currently unoccupied have the high probability of being invaded in the near future. This means that Kanto and northern Kyushu areas have the higher potential risk of nutria invasion. By predicting the areas with higher risk of nutria invasion, my study helped to determine where to focus regulation efforts in Japan. This will also help us make a plan of how to prevent the expansion of nutria population into these areas and help the appropriate management of nutria population in Japan. Therefore, my study would be useful for the management and control plan of nutria in Japan when carefully used with the consideration for the limitations and further possible studies.

Limitations and Future Directions

My study's quality can be affected by several limitations. Firstly, invasive species usually violate the equilibrium assumption of SDM which impacts the accuracy of the predicted potential distribution range of nutria. The SDM assumes that the target species are in the equilibrium in their environment, but invasive species tends to violate this assumption because they are in the non-native environment. Nutria in Japan are also in their non-native environment, and the accuracy of my prediction of their potential distribution might be affected by this violation (Gallien 2012). To overcome this limitation, the further studies should be conducted with other prediction models or with true-absence data of the species. Some studies found that using the distribution model in a risk assessment framework with the effort of close monitoring or using true-absence data in the model increased the accuracy of the distribution prediction of invasive species (Václavík and Meentemeyer 2009 & Jones 2012).

Also, my models are the prediction for potential nutria distribution in the current environment and are limited as the distribution prediction in the future environment. This is because I only used the current climatic data for my modeling. The invasive species' violation of the SDM assumption tends to lead the decline in the accuracy of the prediction model as the future distribution prediction (Jones 2012). Moreover, the environmental conditions might change over time, and this would change the potential habitat range of the nutria in the future. Indeed, a previous study found that the nutria's potential distribution range in Bolleswood Natural Area, Connecticut, USA changed with the different climate change scenarios (Jarnevich et al. 2017). The potential distribution of nutria in Japan might be affected by the change in climate as well. Therefore, change in climatic variables of my study might alter the potential distribution ranges of nutria in Japan over time. The studies to forecast the future distribution of nutria by using the data of future environmental scenarios should also be conducted because knowing possible future distribution will help the management of nutria be more efficient.

Another limitation would be the absence of other possible factors that affect the nutria distribution pattern in my study. Previous studies have found that human densities, human activities, and urbanization affect the distribution pattern of nutria. Nutria tend to avoid the areas with higher human density, urbanized areas, and the areas with higher human activities, such as hunting. (Guichon and Cassini 2005 & River 2018 & Bertolino and Ingegno 2009). Including these variables might change the prediction results because I only included climatic variables this time. In the further studies, the nutria's potential distribution could be predicted with other environmental variables, such as hydrology or human footprint so that we could know more realistic distribution of nutria in Japan.

Broader Implication

This study improved the knowledge about the possible areas with the higher risk of nutria invasion in Japan in terms of potential distribution of nutria, which created the opportunity to move forward the nutria management and control in Japan. My study indicates that nutria may continue to expand their range in Japan and identifies the regions most at risk for invasion. This knowledge can be used by scientists and policymakers to reduce further nutria impact in Japan.

This study also revealed the possible effects of performing SDM over space on the prediction quality and the importance of knowing possible distribution of invasive species for their regulations. These findings will help us improve the situations of the other invasive species whose potential distribution range are not well understood in Japan. The studies with different distribution models, with future environmental scenarios, and with different factors that affect the invasive species distribution pattern should be conducted for the other invasive species as well as nutria. Scientists, biologists, and Japanese government can keep monitoring the distribution pattern of invasive species in the areas with their higher potential distribution to improve the invasive management situation and prevent the further spread and impact of invasive species in Japan.

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