A THESIS FOR THE DEGREE OF
MASTER OF SCIENCE

Predicting distribution of *Piezodorus hybneri* (Gmelin) (Hemiptera: Pentatomidae) in Korea under climate change using the Maxent model

Maxent 모델을 이용한 기후변화에 따른 가로줄노린재의
한국에서의 분포예측

BY
Aejin Hwang

ENTOMOLOGY PROGRAM
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Aejin Hwang

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BY THE COMMITTEE MEMBERS

Chairman	Dr. Seunghwan Lee	____________________
Vice Chairman	Dr. Joon-Ho Lee	____________________
Member	Dr. Kwang Pum Lee	____________________

ABSTRACT

Predicting distribution of *Piezodorus hybneri* (Gmelin) (Hemiptera: Pentatomidae) in Korea under climate change using the Maxent model

Aejin Hwang

Entomology program, Department of Agricultural Biotechnology

Seoul National University

Piezodorus hybneri (Hemiptera: Pentatomidae) is one of the major soybean pests, and distributed mostly in the southern region in Korea. However, the climate change may change the current distribution of *P. hybneri*. The species distribution model (SDM) is often used to predict potential distribution of insects. In this study, we used the representative concentration pathway (RCP) 8.5 scenario and the Maxent model, which is one of the SDMs, to predict distribution of *P. hybneri* in Korea under climate change.

Thirty four occurrence points were applied for model calibration, which were collected from specimen data in Jeju and field survey. Occurrence data for model validation were collected from scientific articles and National Ecosystem Survey reports in Korea. To avoid sampling bias, Average Nearest Neighbor distances among occurrence points were calculated using ArcGIS 10.1 and the Rarefy Occurrence Data at SDMs (species distribution models) tool on ArcGIS 10.1 was used. As a result, 12 occurrence points were used for model validation to predict distribution of *P. hybneri*.

By using DIVA-GIS 7.5 19 bioclimatic variables were generated from 2001-2010 (2000s) climate data and 2031-2040 (2030s), 2051-2060 (20-50s), 2071-2080 (2070s), 2091-2100 (2090s) climate data from the RCP 8.5 scenario. Then, these variables were applied to the Maxent model, and through variable selection process, 4 variables were selected: Annual mean temperature, temperature seasonality, mean temperature of wettest quarter and mean temperature of coldest quarter. Finally, by using the Maxent model and these four variables, potential distribution of *P. hybneri* in current (2000s) and future climate condition was predicted.

Among 4 variables, mean temperature of wettest quarter and mean temperature of coldest quarter were most important.

In conclusion, following prediction was made for distribution of *P. hybneri* in Korea. The suitable habitat area for *P. hybneri* was 20,710 km^2 in 2000s, locating in the southern coastal areas and southern part of western coastal areas. Suitable habitats were extended to north-east bound by climate change, as 41,599 km^2 in 2030s, 68.404 km^2 in 2050s, 83,336 km^2 in 2070s and 89,062 km^2 in 2090s. In 2090s, most parts of Korea except for the mountain region were suitable for *P. hybneri*. .

Key words: *Piezodorus hybneri*, climate change, distribution, Maxent model

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Ⅰ. Introduction

Piezodorus hybneri (Gmelin) is one of the important soybean pests in Korea (Son et al., 2000; Paik et al., 2007) and Japan (Kobayashi, 1972; Kono, 1989; Higuchi, 1992; Osakabe and Honda, 2002). It was denominated as *Cimex* (= *Piezodorus*) *rubrofasciatus* at a first time (Fabricius, 1787), but renamed as *Cimex* (= *Piezodorus*) *hybneri* (Gmelin, 1789). It is currently known that *P. hybneri* distributes in Korea (Son et al., 2000; Oh, 2007; Paik et al., 2007a, b), Japan (Kobayashi, 1981), Taiwan (Wang, 1980), India (Panizzi, 1997), Indonesia (van den Berg et al., 1995), Philippines, Nepal (Bae et al., 2005), and North Africa (Kobayashi, 1972). In Korea, *P. hybneri* occurs in mostly southern regions due to the low temperature during winter (Bae et al., 2005).

Adults of *P. hybneri* move to soybean fields around the pod development stage of soybean (Setokuchi et al., 1986; Higuchi, 1992; Paik et al., 2007; Son, 2009) and lay eggs on soybean pods (Higuchi, 1994b). It was observed in the field conditions that one female laid average 9.5 egg masses which had approximately 25 eggs per egg-mass (Higuchi and Mizutani, 1993). The egg development period was 3-5 days. *P. hybneri* can complete its development through five nymphal stages, and development period from the first instar to adult was observed from 16 to 21 days in the field conditions (Kobayashi, 1972). Lower developmental threshold temperature and effective accumulate temperature of *P. hybneri* from egg to adult were estimated as 10.7℃ and 386.4 DD, respectively (Paik et al, 2005). New generation adults emerged around the seed development stage (Higuchi, 2002). The decreased photoperiod to 13L: 11D might cause the populations of *P. hybneri* to diapause with lowering temperature (Kikuchi and Kobayashi, 1984; Higuchi, 1994a). The overwintering survival rate was observed as 43.9% in Japan (Kikuchi, 1996) but it might be much lower in colder regions.

Stink bugs such as *P. hybneri*, *Halyomorpha halys, Nezara antennata Dolycoris baccarum* (Hemiptera: Pentatomidae) and *Riptortus clavatus* (Hemiptera: Alydidae) damage bean plants by piercing and sucking the pods or seeds. Damage by these stink bugs causes yield loss and quality decrease (Suzuki et al., 1991; Oh, 2007; Son, 2009). According to Wada et al. (2006), 27.8 ~ 43.3% of soybean seeds were damaged by stink bugs in the National Agricultural Research Center for Kyushu Okinawa Region (KONARC) soybean fields in 2003. From the results of survey conducted in soybean fields of six regions in Gyeongbuk Province, average 18.7% of pods and 28.1% of seeds were damaged by stink bugs (Son, 2009).

Moreover, *P. hybneri* can transmit the causative agent of yeast-spot disease of soybean, *Eremothecium coryli*, which is also carried by *R. clavatus, N. antennata and D. baccarum* (Kimura et al., 2008). Therefore, *P. hybneri* might cause serious problems in bean productions in a case that the populations invade new regions as the global temperature is increasing continuously.

From 1880 to 2012, global temperature increased by approximately 0.85℃ (IPCC, 2014). In Korea, the temperature increased by 0.23℃ per 10 years from 1954 to 1999. However, the temperature increase showed a tendency to be accelerated by increasing by 0.41℃ from 1981 to 2010 and by 0.5 ℃ from 2001 to 2010 (KMA, 2014). These sharp climate changes were unprecedented. The representative concentration pathways (RCP) scenario by the intergovernmental panel on climate change (IPCC) showed possible a future climate, depending on the amount of emitted greenhouse gases. For example RCP 8.5 assumes that greenhouse gas emissions are similar to present. In this condition, the global temperature might increase more sharply (IPCC, 2014).

Distribution of insects is affected by climate. Especially, temperature is an important factor to determine insect distribution because insects are poilkilotherms (Musolin and Fujisaki, 2006). The temperature increase causes the changes in the developmental rate, migration or movement, overwintering survivorship of insects, which directly affect distribution of insects (Bale et al., 2002). Until now, the changes of distributional range in multiple insect species were most obviously and clearly detected by global warming (Parmesan, 2001).

For developing proper pest management strategies under global warming, the changes of distributional range of pests should be understood. Species distribution models (SDMs) can be used for predicting potential distribution of insects which is largely and clearly affected by climate changes. SDM predicts potential distribution of species based on environmental variables of occurrence sites (Franklin, 2010).

One of popularly used SDMs is the Maxent model which is based on maximum entropy. Maximum entropy means most spread out or closest to uniform (Phillps et al, 2006). Therefore, the Maxent model can predict the distribution of a species by estimating the most uniform distribution of the species in the given conditions. The Maxent model uses only presence data for occurrence data, and can use both continuous and categorical data for environmental variables. Moreover, the Maxent model is less affected even when sample size of occurrence data for model calibration is small (Phillps et al, 2006), allowing its effective use when available data are limited.

Spatial distribution of *P. hybneri* was studied only in local areas (Kono, 1990; Higuchi, 1992), and these studies focused on spatial distribution within a field. These information might be very useful to determine site-specific management of *P. hybneri* within a field. However, it is required to define its nationwide distribution in order to forecast the invasion of *P. hybneri* to new regions in the country and this would allow us to determine effects of global warming on distributional range changes of *P. hybneri* in the future.

In Korea, no studies were attempted to define current distribution or prediction future distribution of *P. hybneri.* However, there were a few field surveys of *P. hybneri* in local soybean fields (Son et al, 2000; Oh, 2007; Paik et al, 2007b; Son, 2009; Seo et al, 2011) and fallow paddy fields (Paik et al, 2007a, Paik et al, 2009). *P. hybneri* was recorded from the survey of insect fauna in Busan (Park et al, 2009), Jinju, Gyeongsangbuk-do (Lim and Park, 2009), Junam wetland area (Ahn and Park, 2012; Ahn, 2013), and Ulleung-do (Lee et al, 2006). This localized information is not enough to prepare management strategies for *P. hybneri* and to predict its distribution in the future.

Therefore, this study was conducted to predict distribution of *P. hybneri* in Korea under climate change using the Maxent model.

Ⅱ. Materials and Methods

2-1. Species occurrence data

Two sets of occurrence data for *P. hybneri* were used for Maxent modeling. One was used for model calibration and the other was used for model validation. Occurrence data for model calibration was generally called as the training data and data for model validation called the test data in the Maxent modeling.

2-1-1. Training data

Field survey of *P. hybneri* was conducted at 102 sites in August and September in 2015 (Fig. 1). Presence of *P. hybneri* was surveyed in the soybean fields by naked eye observation. Among 102 sites, *P. hybneri* was found at 32 sites. Two records in Jeju Island were collected from specimen data of National Institute of Agricultural Sciences Insect Collection (http://insect.naas.go.kr). Therefore, 34 points were used for model calibration (Table 1 and Fig. 2).

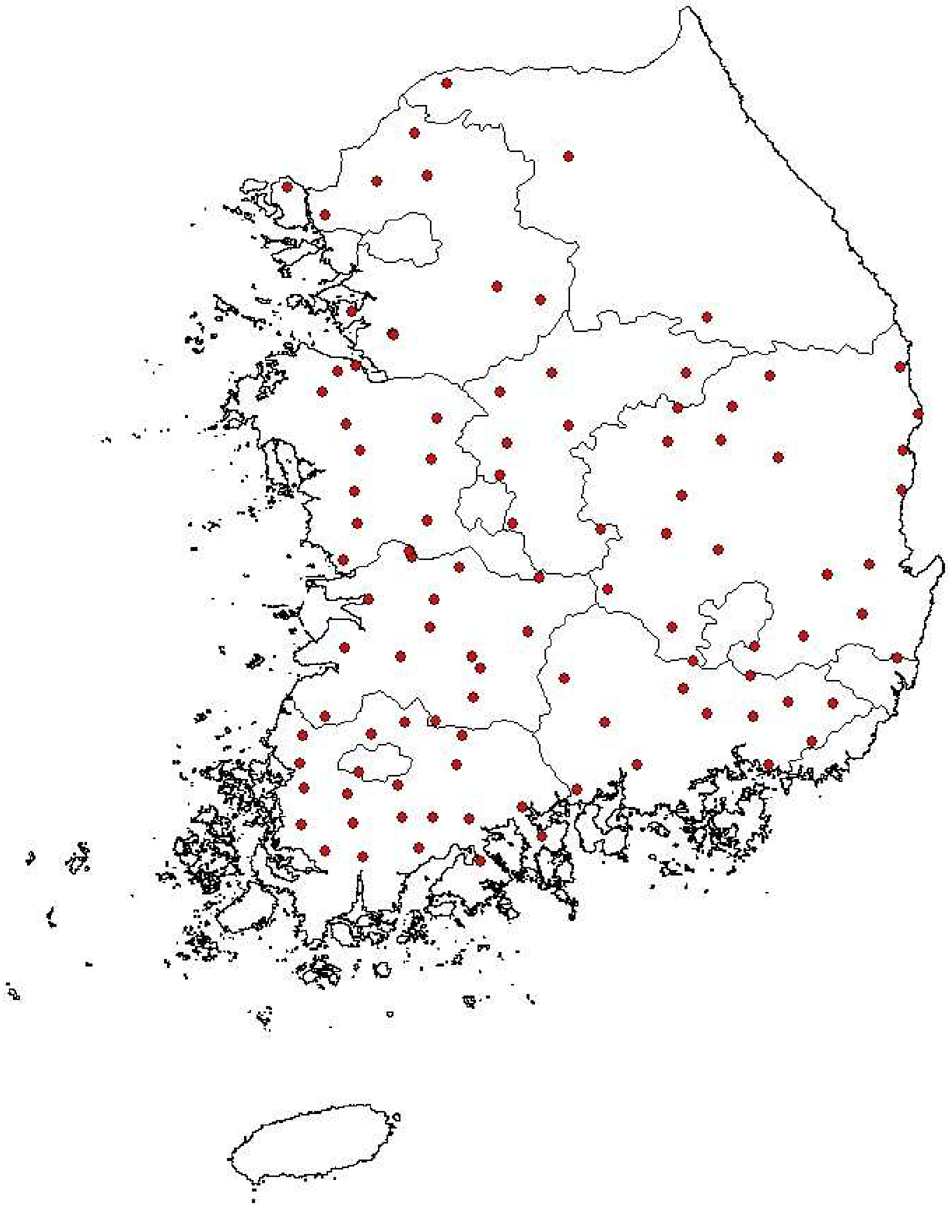

Figure 1. Map of survey sites for *Piezodorus hybneri*

Table 1. Information of the training data of *P. hybneri* in Korea

Locality	Dates	Coordinates		Source
		Longitude	Latitude	
Dangjin-si, Chungcheongnam-do	18-Aug-2015	N 36° 50′ 18″	E 126° 36′ 3.8″	Field survey
Buan-gun, Jeollabuk-do	19-Aug-2015	N 35° 39′ 49.4″	E 126° 42′ 21.2″	
Jeongeup-si, Jeollabuk-do	18-Aug-2015	N 35° 37′ 2.3″	E 126° 58′ 44″	
Gochang-gun, Jeollabuk-do	19-Aug-2015	N 35° 20′ 41.6″	E 126° 36′ 46″	
Jangseong-gun, Jeollanam-do,	19-Aug-2015	N 35° 15′ 53.3″	E 126° 50′ 18.2″	
Yeonggwang-gun, Jeollanam-do,	19-Aug-2015	N 35° 15′ 21.1″	E 126° 30′ 16.3″	
Gwangsan-gu, Gwangju	19-Aug-2015	N 35° 5′ 31.2″	E 126° 46′ 33.3″	
Naju-si, Jeollanam-do,	20-Aug-2015	N 34° 59′ 28.6″	E 126° 43′ 23.2″	
Yeongam-gun, Jeollanam-do	19-Aug-2015	N 34° 43′ 23.6″	E 126° 37′ 1.8″	
Boseong-eup, Boseong-gun, Jeollanam-do	20-Aug-2015	N 34° 44′ 21.7″	E 127° 3′ 57.8″	
Hwasun-gun, Jeollanam-do	20-Aug-2015	N 34° 52′ 50.1″	E 126° 59′ 2″	
Bongnae-myeon, Boseong-gun, Jeollanam-do	20-Aug-2015	N 34° 52′ 53.3″	E 127° 7′ 42.5″	
Beolgyo-eup, Boseong-gun, Jeollanam-do	20-Aug-2015	N 34° 52′ 37.5″	E 127° 18′ 25.3″	
Suncheon-si, Jeollanam-do	20-Aug-2015	N 34° 55′ 46.3″	E 127° 33′ 37.2″	
Sunchang-gun, Jeollabuk-do	20-Aug-2015	N 35° 19′ 29.2″	E 127° 8′ 35.5″	
Wanju-gun, Jeollabuk-do	21-Aug-2015	N 36° 1′ 37.3″	E 127° 15′ 25.6″	
Nonsan-si, Chungcheongnam-do	21-Aug-2015	N 36° 14′ 31.6″	E 127° 6′ 21.7″	
Gyeongju-si, Gyeongsangbuk-do	18-Aug-2015	N 35° 48′ 52.7″	E 129° 11′ 36.2″	
Yangsan-si, Gyeongsangnam-do,	19-Aug-2015	N 35° 24′ 20.5″	E 129° 3′ 24.1″	
Gimhae-si, Gyeongsangnam-do	19-Aug-2015	N 35° 13′ 54″	E 128° 57′ 7.5″	
Jinhae-gu, Changwon-si, Gyeongsangnam-do	19-Aug-2015	N 35° 7′ 10.6″	E 128° 44′ 48.4″	
Uichang-gu, Changwon-si, Gyeongsangnam-do	19-Aug-2015	N 35° 20′ 34.7″	E 128° 40′ 4.5″	
Miryang-si, Gyeongsangnam-do	19-Aug-2015	N 35° 24′ 49″	E 128° 50′ 29″	
Haman-gun, Gyeongsangnam-do	20-Aug-2015	N 35° 21′ 22.5″	E 128° 26′ 50.4″	
Uiryeong-gun, Gyeongsangnam-do	20-Aug-2015	N 35° 28′ 17.8″	E 128° 20′ 1.9″	
Changnyeong-gun, Gyeongsangnam-do	20-Aug-2015	N 35° 35′ 54.2″	E 128° 22′ 59.2″	
Goryeong-gun, Gyeongsangbuk-do	20-Aug-2015	N 35° 45′ 18.7″	E 128° 16′ 49.6″	
Sancheong-gun, Gyeongsangnam-do	27-Aug-2015	N 35° 19′ 3.8″	E 127° 57′ 25.6″	
Jinju-si, Gyeongsangnam-do	27-Aug-2015	N 35° 7′ 10.7″	E 128° 6′ 54.1″	
Hadong-gun, Gyeongsangnam-do,	27-Aug-2015	N 35° 00′ 29.2″	E 127° 49′ 30.2″	
Yeosu-si, Jeollanam-do	26-Aug-2015	N 34° 47′ 25.4″	E 127° 39′ 15.5″	
Hwasun-gun, Jeollanam-do	26-Aug-2015	N 35° 1′ 34.4″	E 126° 57′ 42.3″	
Bukjeju-gun, Jeju-do	1990	N 33° 29′ 20″	E 126° 29′ 54″	http://insect.naas.go.kr
Gujwa-eup, Bukjeju-gun, Jeju-do,	1990	N 33° 31′ 21″	E 126° 51′ 6″	

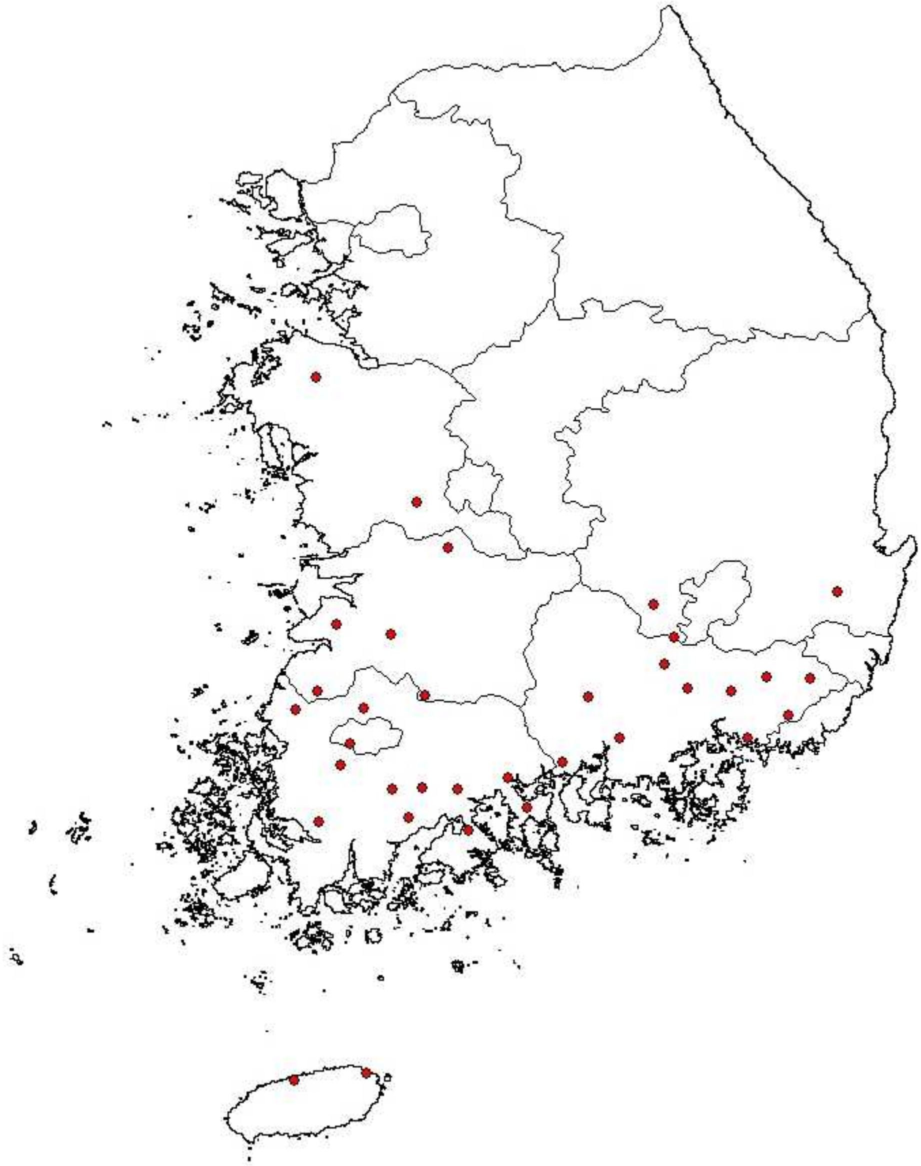

Figure 2. Map of occurrence sites of training data for *P. hybneri*

2-1-2. Test data

Forty three records (Table 2) were collected from scientific articles (Paik at el. 2005; Lee et al. 2006; Lim and Park, 2009; Park et al. 2009; Seo at el., 2011; Ahn and Park, 2012; Ahn, 2013), National Ecosystem Survey reports by Ministry of Environment in Korea from 2001 to 2015. In the collection of data, records in islands except for Jeju Island and doubtful records which were located far outside of the known range were removed.

Sampling bias was measured by calculating Average Nearest Neighbor distance using ArcGIS 10.1 (ESRI, 2012). The spatial distribution of *P. hybneri* was aggregated at 95 percent confidence level when the data was analyzed with Average Nearest Neighbor distance (Fig. 3 and Table 3). Because Maxent modeling requires the random distribution data, additional processing of collected data was executed with Rarefy Occurrence Data at SDMs (species distribution models) tool (Brown, 2014) on ArcGIS 10.1 (ESRI, 2012).

The function, Spatially Rarefy Occurrence Data at SDMs tool on ArcGIS 10.1 might help to avoid sampling bias (Brown, 2014). The Spatially Rarefy Occurrence Data at SDMs tool spatially filters local data by user input distance, reducing occurrence localities to a single point within specified Euclidian distance (Brown, 2014). The value of expected mean distance (0.269095 decimal degrees) which is average of distance between nearest points when points are randomly distributed from Average Nearest Neighbor (ESRI, 2012) was used for input distance. From these procedures, the number of occurrence points was reduced to 12 points. These occurrence points were used for model validation (Fig. 4).

Table 2. Number of collected points of *P. hybneri*

	Number of points
Scientific articles	10
National Ecosystem Survey	30
Field occurrence	3
Total	**43**

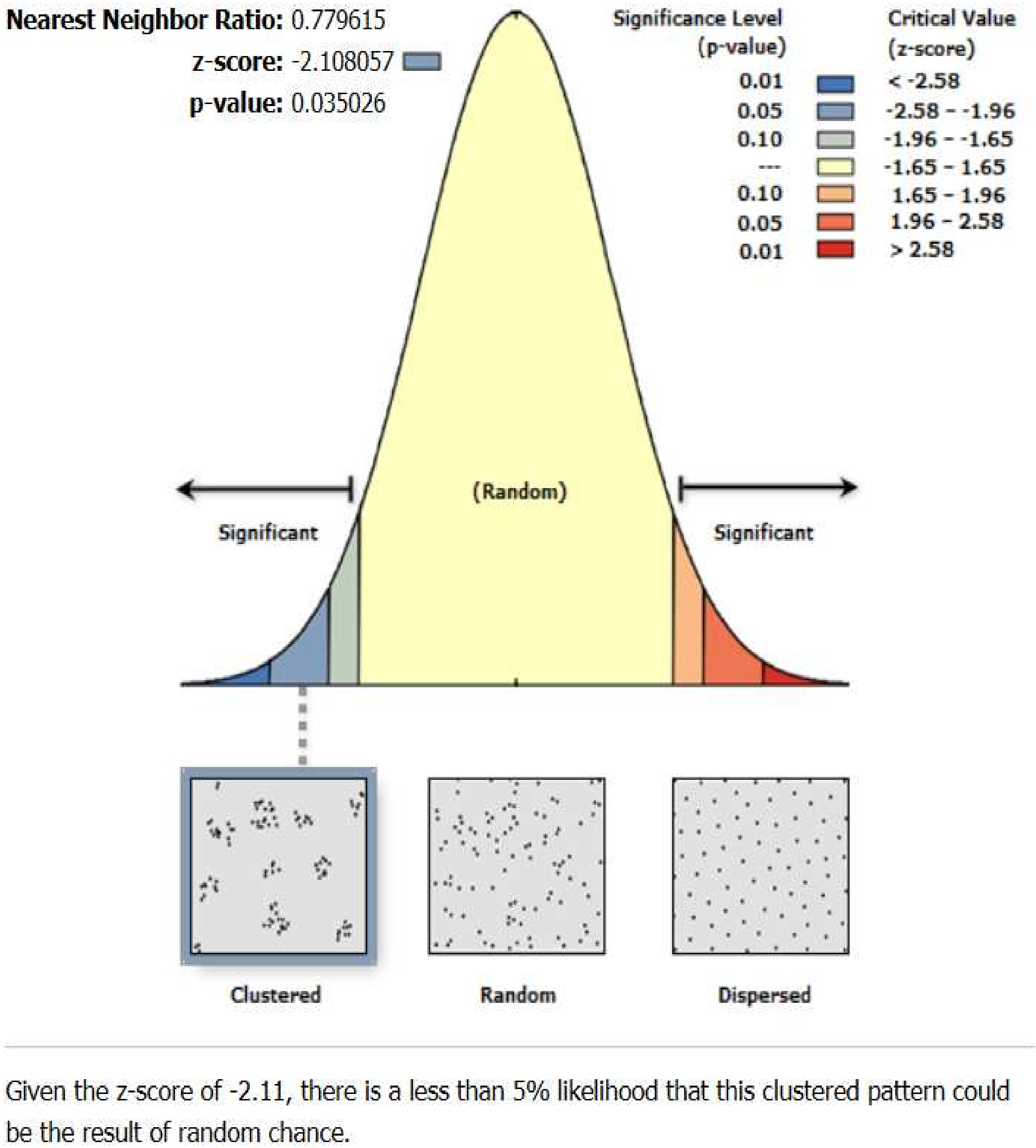

Figure 3. Results of Average Nearest Neighbor for *P. hybneri*

Table 3. Values of Average Nearest Neighbor for *P. hybneri*

Observed Mean Distance	0.209790 Degrees
Expected Mean Distance	0.269095 Degrees
Nearest Neighbor Ratio	0.779615
z-score	-2.108057
p-value	0.035026
	Clustered

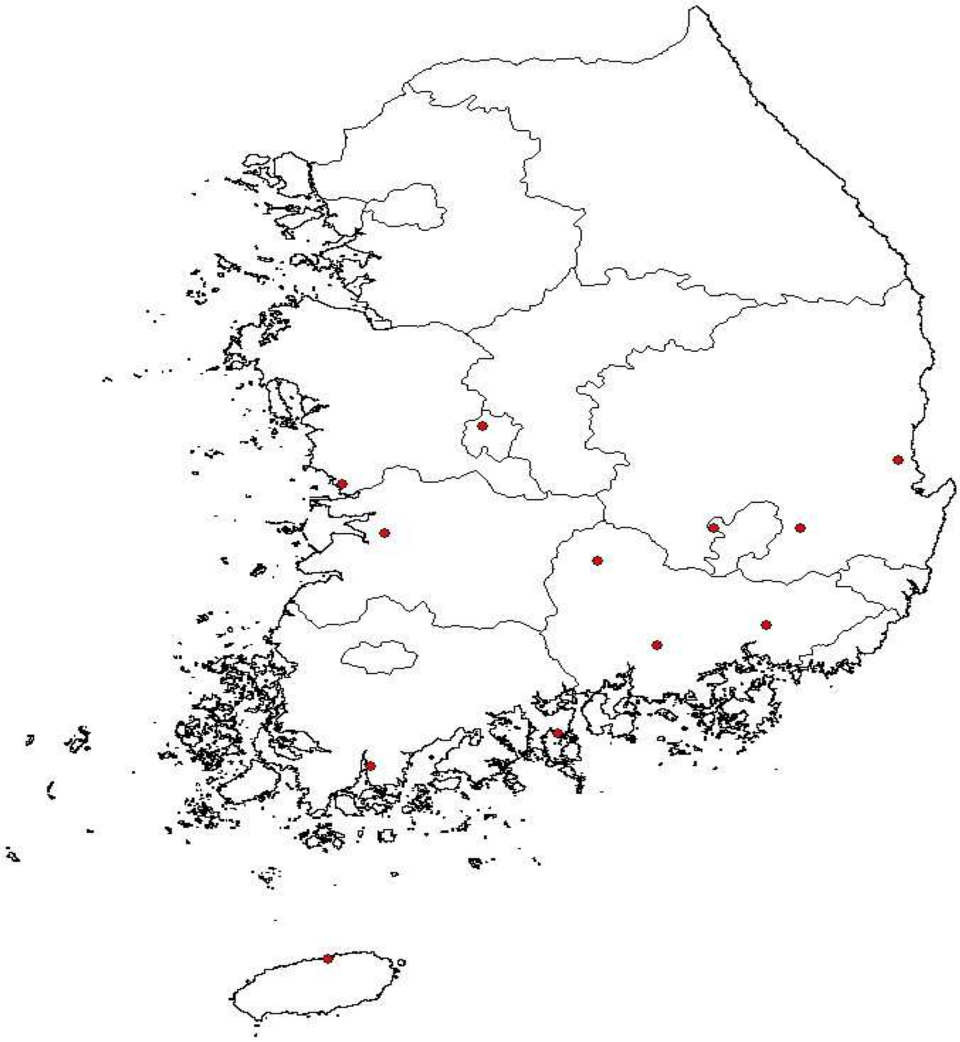

Figure 4. Occurrence points of test data for *P. hybneri*

2-2. Environmental variables

2001-2010 (2000s) climate data based on observation data from Korea meteorological administration (KMA) was used for climate data of occurrence sites. 2031-2040 (2030s), 2051-2060 (2050s), 2071-2080 (2070s), 2091-2100 (2090s) climate data of the RCP 8.5 scenario from KMA was used to predict potential climatic suitability for future. 2001-2010 (2000s) climate data which were estimated by scenario from KMA was used to predict potential climatic suitability for current climate conditions. Resolution of climate data were 1 km grid size.

Monthly minimum, maximum temperature and precipitation data of each climate data were used to create 19 bioclimatic variables (Ramirez-Villegas and Bueno-Cabrera, 2009) using DIVA-GIS 7.5 (Hijmans, 2012). Nineteen bioclimatic variables were shown in Table 4.

Table 4. List of 19 bioclimatic variables

BIO01 = Annual Mean Temperature
BIO02 = Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO03 = Isothermality (BIO2/BIO7) (* 100)
BIO04 = Temperature Seasonality (standard deviation *100)
BIO05 = Max Temperature of Warmest Month
BIO06 = Min Temperature of Coldest Month
BIO07 = Temperature Annual Range (BIO5-BIO6)
BIO08 = Mean Temperature of Wettest Quarter
BIO09 = Mean Temperature of Driest Quarter
BIO10 = Mean Temperature of Warmest Quarter
BIO11 = Mean Temperature of Coldest Quarter
BIO12 = Annual Precipitation
BIO13 = Precipitation of Wettest Month
BIO14 = Precipitation of Driest Month
BIO15 = Precipitation Seasonality (Coefficient of Variation)
BIO16 = Precipitation of Wettest Quarter
BIO17 = Precipitation of Driest Quarter
BIO18 = Precipitation of Warmest Quarter
BIO19 = Precipitation of Coldest Quarter

2-3. Variable selection and evaluation

To select the variables, Maxent modeling with all 19 bioclimatic variables was initially executed. Linear and quadratic feature types were used and the jackknife resampling was conducted to measure variable importance when modeling.

When the area under the curve (AUC) value without a variable among 19 variables was compared with the AUC value with all 19 variables from the results of jackknife test in Maxent modeling, the variable was eliminated if the AUC value with 18 variables was larger than the AUC value with all 19 variables because results of modeling were better when that variable was removed. Revised model was performed and repeated this process until only suitable variables remained.

The performance of the model with selected variables was evaluated using the AUC values of the receiver operating characteristics (ROC) plots. And evaluate selected variables from variable selection process by Jackknife tests, variable response curves, and percent contribution and permutation importance value.

2-4. Prediction of current and future potential distribution

Climate suitability for *P. hybneri* was predicted under the current climate condition (2000s) and future climate scenarios with 2031-2040 (2030s), 2051-2060 (2050s), 2071-2080 (2070s), 2091-2100 (2090s) of the RCP 8.5 scenario using the Maxent model with four selected variables.

At the results of the Maxent model, the value in each grid cell indicates mean climate suitability which had ranges from 0 to 1. Threshold was calculated by the “Maximum training sensitivity plus specificity” rule. When it applied, the sum of false negative and false positive error for training data has minimum value. Calculated threshold value was used for creating binary maps which had value of presence (1) and absence (0) in each grid cell.

Changes between current and future potential habitat were calculated using Distribution Changes Between Binary SDMs at SDMs tool (Brown, 2014) on ArcGIS 10.1.

Ⅲ. Results

3-1. Variable selection and evaluation

Four variables were selected from the variable selection process. Selected variables were annual mean temperature (Bio01), temperature seasonality (Bio04), mean temperature of wettest quarter (Bio08) and mean temperature of coldest quarter (Bio11).

The model's AUC values were 0.899 and 0.820 for training and test data, respectively (Fig. 5). The Receiver Operating Characteristic (ROC) curve showed increase of sensitivity (true positive) when the fractional predicted area increased. Sensitivity largely increased when the predicted area increased, the ROC curve was near to the top-left corner and the AUC had high value. The high AUC values of both training and test data indicated that model performance was good.

According to the percent contribution and permutation importance values of variables (Table 5), Bio08 had the highest percent contribution (75.9) and permutation importance (58.1) and Bio11 had the second largest permutation importance (41.9). Percent contribution means that how much corresponding variable was used in the model calibration, and permutation importance indicate effects on training AUC when corresponding variable was changed.

Results of jackknife tests also showed that Bio08 and Bio11 were important. The variable, Bio08, showed the highest training gain when each variable was used alone for Maxent modeling. It indicates that Bio08 is one of the valuables variable. On the other hand, Bio11 showed the highest decrease in training gain among all cases when one variable was omitted and the other variables were included in Maxent modellings. It also indicates that Bio11 is one of the valuable variables in the distribution of *P. hybneri* (Fig. 6).

Response curves indicated that climate suitability for *P. hybneri* increased when annual mean temperature and mean temperature of wettest quarter increased. Suitability also increased when mean temperature of coldest quarter increased below 4℃. Response curve of temperature seasonality indicated that climate suitability for *P. hybneri* increased when seasonal variability of temperature decreased (Fig. 7).

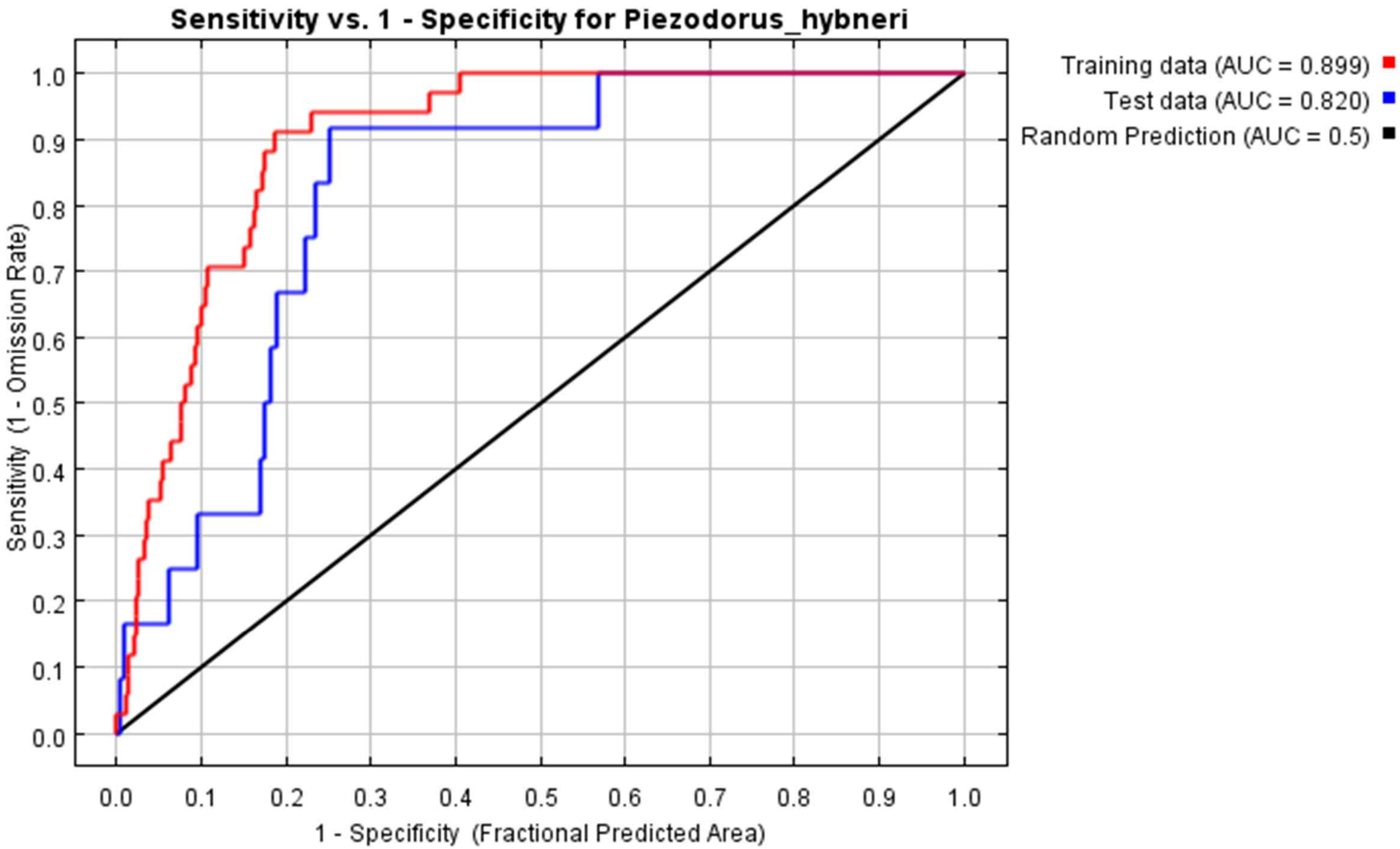

Figure 5.The receiver operating characteristic (ROC) curve for training and test data with the area under the curve (AUC)

Table 5. Maxent model variable contribution

Variable	Percent contribution	Permutation importance
BIO08	75.9	58.1
BIO04	12.4	0
BIO01	7.8	0
BIO11	3.9	41.9

(a)

(b)

(c)

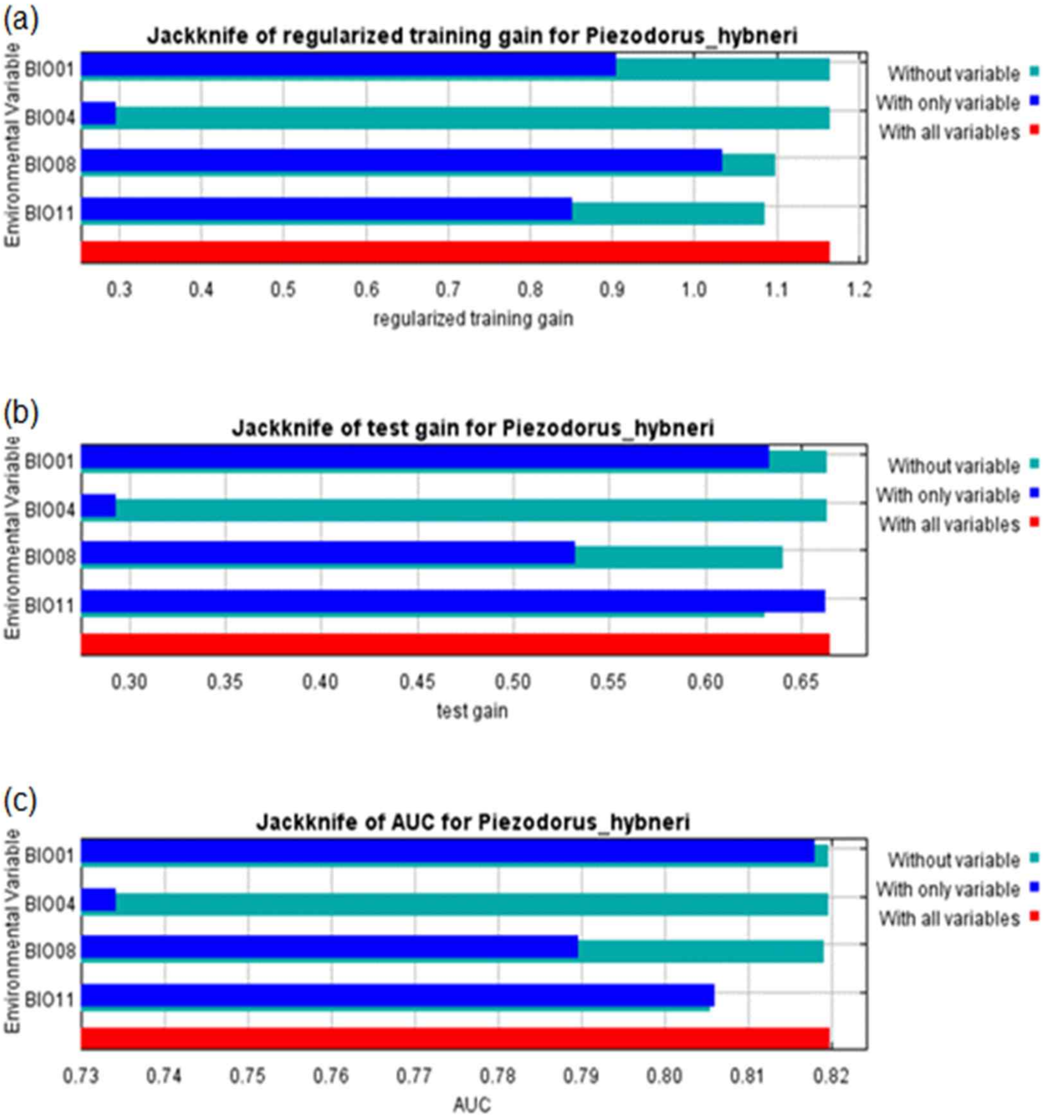

Figure 6. Jackknife test of (a) training gain, (b) test gain and (c) test AUC for *P. hybneri*

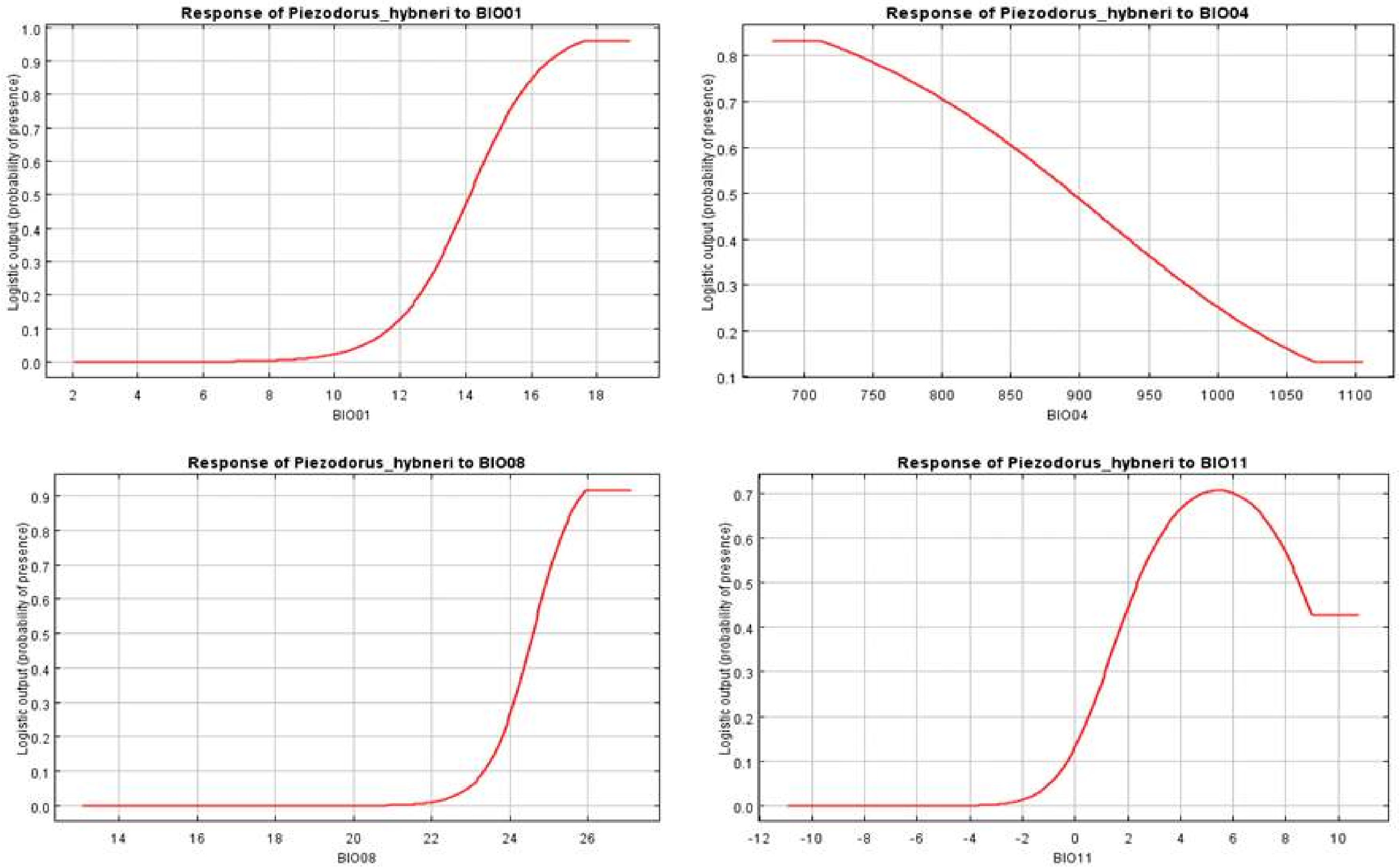

Figure 7. Isolated variable response curve of *P. hybneri*

3-2. Prediction of current and future potential distribution of *P. hybneri*

Climate suitability for *P. hybneri* in current and future climate conditions was mapped over South Korea (Fig. 8). In 2000s, suitability was high in southern coastal areas and southern part of western coastal areas in Korea. Suitability increased with temperature increase.

The value of the “Maximum training sensitivity plus specificity” threshold rule was 0.367 (Table 6). It means that grids with values of 0.367 and higher were considered suitable and below 0.367 were unsuitable for *P. hybneri*. The fractional predicted area (proportion of suitable area) was 0.187, omission (false negative) rates for training and test data were 0.088 and 0.417, respectively, for current distribution at the threshold value of 0.367.

Suitable habitats showed similar tendency to results of climate suitability. Range was expanded to the north-east bound with climate change, from southern coastal areas and southern part of western coastal areas in Korea to most parts of Korea except for the mountain region in 2090s (Fig 9). Area of predicted habitats for *P. hybneri* in 2000s were 20,710 km^2. Area increased with climate change, 41,599 km^2 in 2030s, 68.404 km^2 in 2050s, 83,336 in 2070s and 89,062 km^2 in 2090s (Fig. 10 and Table 7).

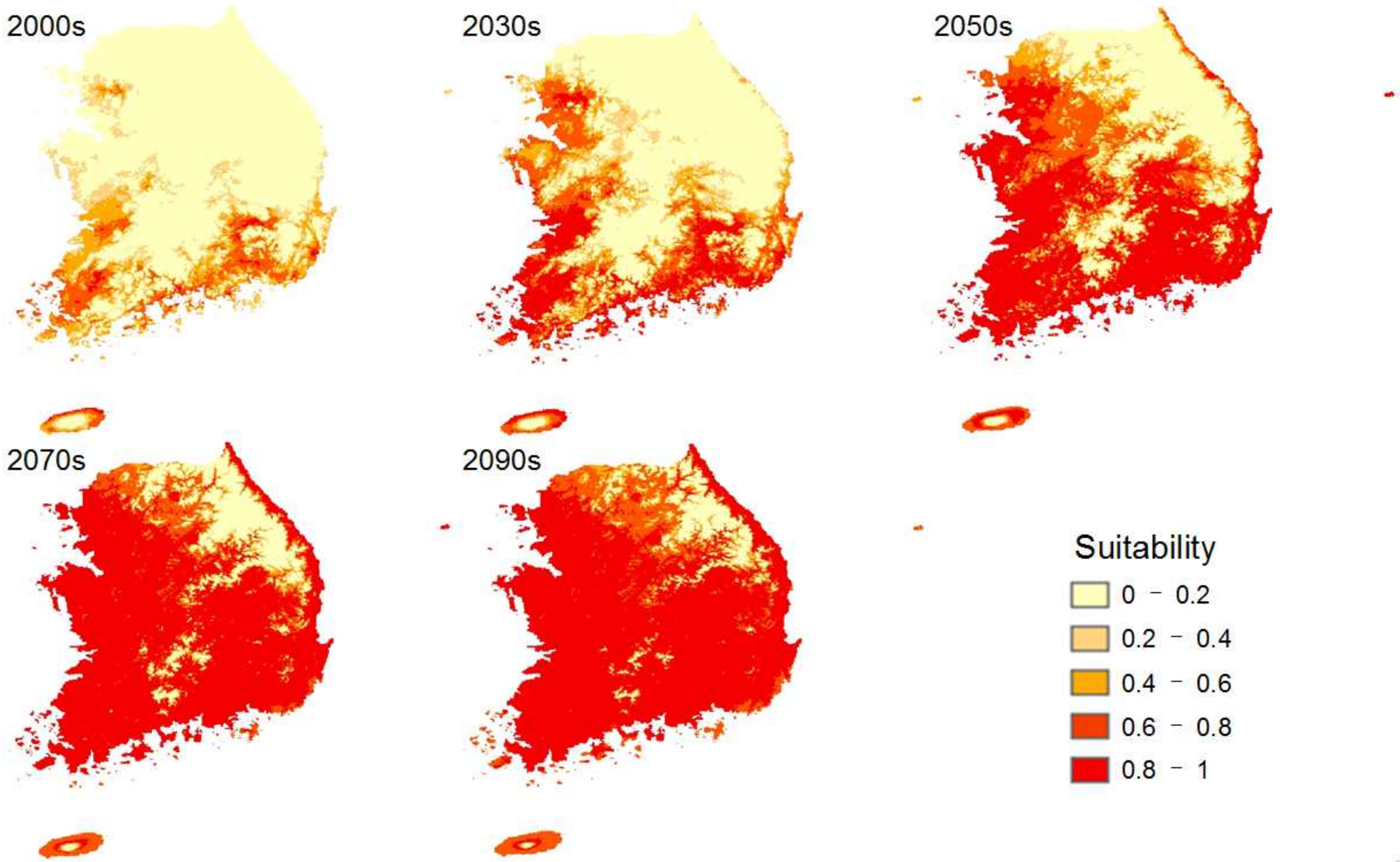

Figure 8. Climate suitability for *P. hybneri* in the 2000s, 2030s, 2050s, 2070s and 2090s under the RCP8.5 scenario

Table 6. Maxent model thresholds, fractional predicted area and omission rate for *P. hybneri*

Cumulative threshold	Logistic threshold	Description	Fractional predicted area	Training omission rate	Test omission rate	P-value
20.773	0.367	Maximum training sensitivity plus specificity	0.187	0.088	0.417	2.572E-3

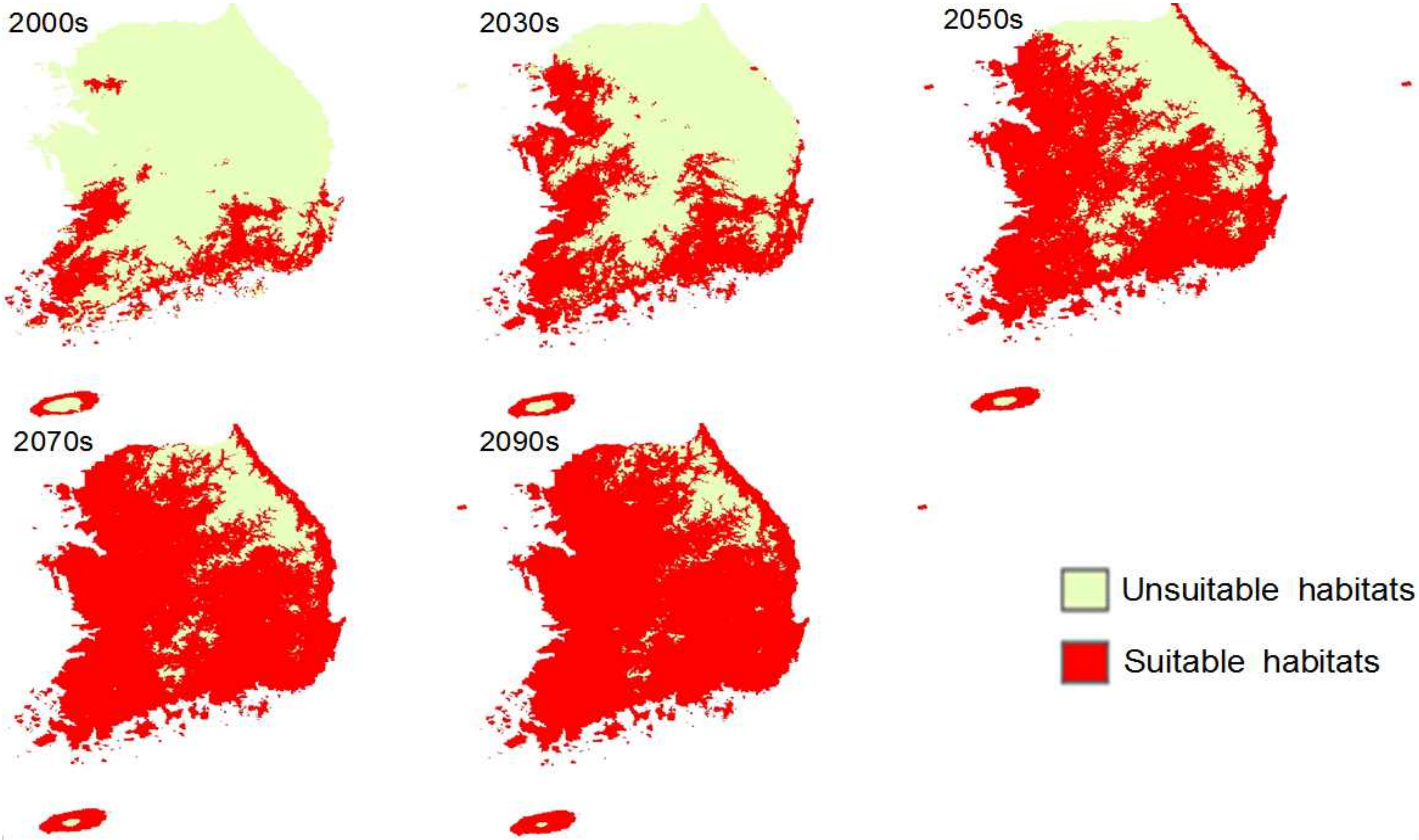

Figure 9. Predicted suitable habitats for *P. hybneri* in 2000s, 2030s, 2050s, 2070s and 2090s under the RCP 8.5 scenario

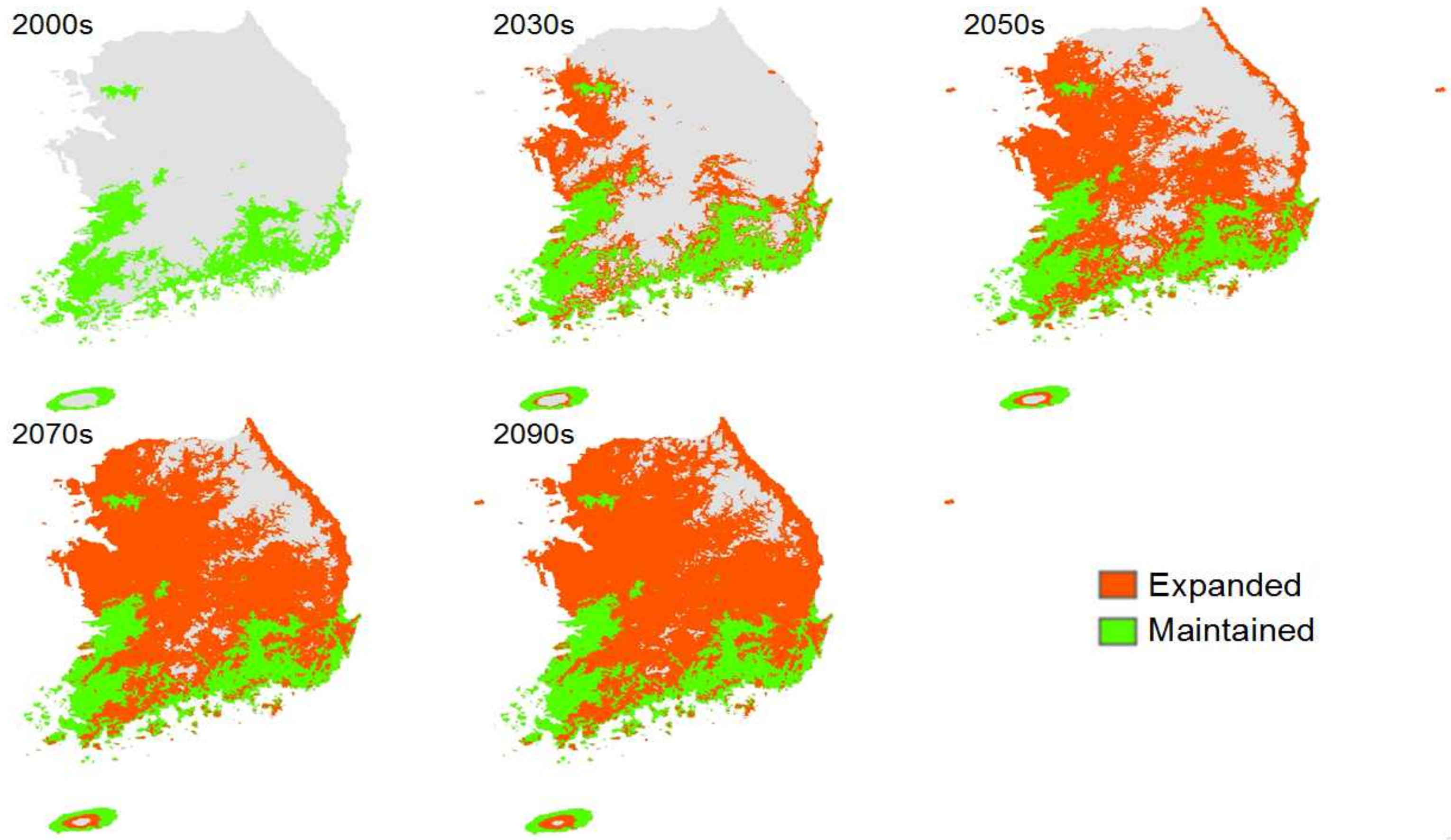

Figure 10. Change of predicted suitable habitat for *P. hybneri* in 2030s, 2050s, 2070s and 2090s based on 2000s habitat prediction under the RCP 8.5 scenario

Table 7. Predicted change (km^2) of *P. hybneri* habitat areas based on 2000s habitat prediction under the RCP 8.5 scenario

	Total area	**Maintained**	**Expanded**	**Contracted**
2000s	20,710			
2030s	41,599	20,708	20,891	2
2050s	68,404	20,710	47,695	0
2070s	83,366	20,710	62,656	0
2090s	89,062	20,710	68,352	0

Ⅳ. Discussion

For prediction of distribution of *P. hybneri* in Korea, four variables among 19 bioclimatic variables were found important: annual mean temperature (Bio01), temperature seasonality (Bio04), mean temperature of wettest quarter (Bio08) and mean temperature of coldest quarter (Bio11). Among them, Bio08 and Bio11 were most important.

Wettest quarter represents July, August, and September in Korea from climate data used in this study. Temperature of warmer season of the year is related to development of insects which, in turn, affects distribution of insects (Bale et al., 2002). *P. hybneri* was favored by increase of Bio08 in this study. The current results coincide with results of Higuchi (1994a) and Bae et al (2005). Development rate of *P. hybneri* increased with temperature increase (Higuchi, 1994a; Bae et al, 2005). Winter temperature acts as a limiting factor to distribution of insects by affecting insect's mortality (Bale, 2002). Suitability increased when Bio11 increased below 4℃ from the response curve in this study. This result is supported by Kicuchi (1996). *P. hybneri* showed high mortality with low winter temperature through 1984 to 1996 according to Kicuchi (1996).

Temperature factors such as Bio01, Bio08, and Bio11 had higher value through southern and western coastal areas in Korea than northern and eastern parts of Korea, and Bio04 had large value in areas far from the coastal areas in the current climate condition. In this study, southern coastal areas and southern part of western coastal areas in Korea were predicted as suitable habitats for *P. hybneri* in the current climate, because suitability for *P. hybneri* increased with increase of Bio01, Bio08, and Bio11 and decrease of Bio04. This result is consistent with observations of previous studies (Son et al, 2000; Bae et al, 2005; Oh, 2007; Paik et al, 2007b; Lim and Park, 2009; Park et al, 2009; Son, 2009; Seo et al, 2011; Ahn and Park, 2012: Ahn, 2013). According to Bae et al (2005), *P. hybneri* occurred in Gyeongsangnam-do, Jeollanam-do and Jeollabuk-do which were southern regions of Korea. From the studies on insect pests in crop or regional insect fauna, *P. hybneri* were found in regions of which latitude were below 37 degrees north (Son et al, 2000; Oh, 2007; Paik et al, 2007b; Lim and Park, 2009; Park et al, 2009; Son, 2009; Seo et al, 2011; Ahn and Park, 2012: Ahn, 2013). *P. hybneri* was founded at Ulleung-do (Lee et al, 2006), although it was located above 37 degrees north. We speculate that Ulleung-do might has high Bio01, Bio08 and Bio11 value and low Bio04 value.

From 2000s to 2090s, values of Bio01, Bio08 and Bio11 increased significantly while the value of Bio04 increased slightly. Area which had high value of Bio01, Bio08 and Bio11 expanded to north-east, and accordingly distribution range of *P. hybneri* was extended to north-east bound with climate change in this study. Similarly, distribution of Heteroptera expanded to poleward under climate change (Judd & Hodkinson, 1998; Musolin, 2007). Similar species, *Nezara viridula* (Hemiptera: Pentatomidae) was shifted 70km^2 north in Japan with winter temperature were increased by 1-2℃ (Musolin, 2007). Two heteropteran species in other genus, *Ischnodemus sabuleti* and *Peritrechus nubilus* (Hemiptera: Lygaeidae) were expanded northward in the United Kingdom (Judd and Hodkinson, 1998).

In conclusion, potential distribution of *P. hybneri* was southern coastal areas and southern part of western coastal areas in Korea under the current climate, and distribution range was predicted to extend to north-east bound under global warming. Result from this study may be used for developing pest management strategy of *P. hybneri*. However, environmental variables used in this study are bioclimatic variables based on temperature and precipitation. To clarify the distribution of *P. hybneri* more precisely, further study may be needed to include other environmental factor such as vegetation.

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국문 초록

Maxent 모델을 이용한 기후변화 따른 가로줄노린재의 한국에서의 분포 예측

황애진
서울대학교
농생명공학부 곤충학전공

가로줄노린재는 콩의 주요 해충으로, 한국에서는 주로 남부지방에 분포하는 것으로 알려져 있으나 기후변화는 가로줄노린재의 분포에 영향을 미칠 수 있다. 이러한 곤충의 분포를 예측하기 위해서 종 분포모델이 많이 이용된다. 본 연구에서는 RCP 8.5 시나리오와 널리 이용되는 종 분포 모델인 Maxent 모델을 이용하여 기후변화에 따른 가로줄노린재의 분포를 예측하였다.

야외조사와 제주지역의 표본자료를 이용하여 수집된 34 개 분포자료를 모델 구동에 이용하였으며, 모델 검증에 이용되는 출현자료는 논문과 환경부 전국자연환경조사 자료를 검토하여 수집한 후, ArcGIS 10.1 의 Average Nearest Neighbor 와 Rarefy Occurrence Data at SDMs 를 이용하여 샘플링 과정에서의 오차를 줄여 최종적으로 총 12 개 분포자료를 모델 검증에 이용하였다.

2000 년대 (2001-2010) 기상자료와 RCP 8.5 시나리오의 2030 년대 (2031-2040), 2050 년대 (2051-2060), 2070 년대 (2071-2080), 2090 년대

(2091-2100) 자료를 이용하여 DIVA-GIS 7.5 를 사용해서 19 개 생물기후변수를 생성하였다. 이들 중 변수 선정 과정을 거쳐 다음과 같은 4 개의 생물기후 변수들을 선정하였다: 연중 평균기온, 기온계절성, 가장 습한 분기의 평균기온 그리고 가장 추운 분기의 평균기온. 선정된 변수들을 이용하여 2000 년대와 2030 년대, 2050 년대, 2070 년대, 2090 년대의 가로줄노린재의 분포를 예측하였다. 선정된 변수들 중 가장 습한 분기의 평균기온과 가장 추운 분기의 평균기온이 중요하였다. 연중 평균기온과 가장 습한 분기의 평균기온이 높을수록, 4℃ 이하에서 가장 추운 분기의 평균기온이 증가할수록 가로줄노린재의 분포에 적합한 것으로 나타났으며, 반면 기온계절성은 낮을수록 가로줄노린재의 분포에 적합하였다.

가로줄노린재의 분포적합지역은 2000 년대에는 20,710km^2 로, 남부지방 및 남해안과 서해안 지역을 따라 형성되었으나, 기후변화에 따라 분포적합지역이 2030 년대에는 41,599 km^2, 2050 년대에는 68.404 km^2, 2070 년대에는 83,336 km^2 로 점점 증가하여 2090 년대에는 89,062 km^2 로, 남한에서 산간지역을 제외한 대부분의 지역이 가로줄노린재의 분포에 적합하였다.

주요어: 가로줄노린재, 기후변화, 분포, Maxent 모델