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Northward Range Expansion of Southern Butterflies According to Climate Change in South Korea

Adhikari, Pradeep[*] · Jeon, Ja-Young[**] · Kim, Hyun Woo[***] · Oh, Hong-Shik[****] · Adhikari, Prabhat[*****] and Seo, Changwan[******]†

[*]*Research Specialist, Environmental Impact Assessment Team, National Institute of Ecology, Korea*
[**]*Researcher, Ecosystem Service Team, National Institute of Ecology, Korea / PhD student, Landscape Architecture, University of Seoul, Seoul, Korea*
[***]*Research Specialist, Eco Bank Team, National Institute of Ecology, Korea*
[****]*Professor, Interdisciplinary Graduate Program in Advanced Convergence Technology and Science and Faculty of Science Education, Jeju National University, South Korea*
[*****]*Master student, Central Department of Botany, Tribhuvan University, Kathmandu, Nepal*
[******]*Chief Researcher, Division of Ecological Assessment, National Institute of Ecology, Korea*

ABSTRACT

Climate change is one of the most influential factors on the range expansion of southern species into northern regions, which has been studied among insects, fish, birds and plants extensively in Europe and North America. However, in South Korea, few studies on the northward range expansion of insects, particularly butterflies, have been conducted. Therefore, we selected eight species of southern butterflies and calculated the potential species richness values and their range expansion in different provinces of Korea under two climate change scenarios (RCP 4.5 and RCP 8.5) using the maximum entropy (MaxEnt) modeling approach. Based on these model predictions, areas of suitable habitat, species richness, and species expansion of southern butterflies are expected to increase in provinces in the northern regions (>36°N latitude), particularly in Chungcheongbuk, Gyeonggi, Gangwon, Incheon, and Seoul. In comparison to the current rate of habitat expansion, those in 2030, 2050, and 2080 were estimated to be 51.07 ~ 209.26%, 74.23 ~ 264.15%, and 62.32 ~ 858.95% higher, respectively. Our study revealed that southern butterflies are susceptible to climate change and that the northern habitat margin of southern butterflies is shifting northward.

***Key words**: Climate Change, Habitat Expansion, MaxEnt, Species Richness, Southern Butterflies*

1. Introduction

Southern butterflies are indigenous species in the southern regions of South Korea and are specifically found below 36.5° latitudes (Kim et al., 2012, 2020; Kwon et al. 2012). However, recently, some southern species have also been recorded in central and northern regions (Kim et al., 2012; Kwon et al., 2014).Overall, 255 species of butterflies are reported in South Korea, of which the southern butterflies contribute approximately 16.42% of the total butterflies in South Korea (Kim et al., 2012). The southern butterflies are considered to be warm-adapted species, as the climate in the southern region of South Korea is warm and humid compared to that in the central and northern regions.

†**Corresponding author** : dharmascw@nie.re.kr (33657, National Institute of Ecology 1210, Geumgang-ro, Maseo-myeon, Seocheon, Chungcheongnam, Republic of Korea. Tel. +82-41-950-5432)

ORCID Adhikari, Pradeep 0000-0002-4115-6242 Oh, Hong-Shik 0000-0001-6960-0221 Jeon, Ja-Young 0000-0001-8461-3370 Adhikari, Prabhat 0000-0003-3338-8040 Kim, Hyun Woo 0000-0002-2160-0625 Seo, Changwan 0000-0003-4626-0206

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Butterflies have some salient features, such as high diversity, high reproduction rates, short generations, good movement, host specificity, and sensitivity to climate change (Honda and Katao, 2005; Karlsson and Van Dyck, 2009; Manzoor and Sadat, 2013; Kwon et al., 2010; 2014; Lee et al., 2015). Thus, they are widely known as indicators of environmental change, including habitat fragmentation, air pollution, and climate change (Nakamura, 2011; Kwon et al., 2014). They are highly sensitive to bioclimatic variables (Manzoor and Sadat, 2013). Increased temperature affects metamorphosis and several physiological activities of butterflies, e.g., egg laying, larval and pupal development, and survival rate (Davis et al., 2005). Similarly, increased precipitation alters the growth and survival of larvae, pupae, and adults by controlling the phenology of the host plant (Srygley et al., 2010). Therefore, global climate change is considered to be the principle reason for the declining population of butterflies and has been associated with mass mortality at overwintering sites and extirpation related to alternating precipitation levels (Forister et al., 2010; Brave et al., 2012). However, various studies have revealed that butterflies existing at low altitude and latitudes show northern range expansion in response to climate change (Crozier, 2004; Mitikka et al., 2008; Kwon et al., 2014; Macgregor et al., 2019).

Over the last century, the average temperature increase was 0.78°C, and it is expected to rise 2.6 ~ 4.8°C by 2100 (IPCC, 2013). In South Korea, the rate of climate change has been estimated to be higher than the global prediction. Over the last 100 years, the temperature increase was 1.8°C in South Korea, and the average temperature is expected to increase by 0.63°C every ten years until 2100 and by 5.7°C by the end of 2100 (Ministry of Environment, 2019). Thus, the potential impact of climate change on southern butterflies is projected to be high in South Korea.

Species distribution models are powerful tools for simulating the spatial distributions of species, estimating the potential responses of organisms, including insect communities, to climate change and determining species niches based on environmental variables (Elith and Leathwick, 2009; Guillera-Arroita et al., 2015; Senay and Worner, 2019). Among the various species distribution models (SDMs), the maximum entropy (MaxEnt) model is a widely used machine-learning technique that has high estimating accuracy while using a small amount of species presence data and environmental variables (Phillips et al., 2006).

Although several studies have addressed the taxonomy, ecology, geographical distribution, range shift and conservation status of butterflies in South Korea (Choi, et al., 2004; Kim et al., 2012; Kim et al., 2013; Kwon et al., 2013; Kwon et al., 2014; Lee et al., 2015), very few studies to date have focused on predicting climate change impacts on butterfly species (Kwon et al., 2010; Kwon et al., 2014; Li et al., 2014; Lee et al., 2020). Therefore, we aimed to predict the suitable habitat of southern butterflies across the country under climate change conditions. Then, we calculated potential species richness and species expansion in different provinces of South Korea to understand the northward range expansion of southern species. We expect this study to be a reference for establishing management plans to conserve the habitat of southern butterflies.

2. Methods

2.1 Study area

This study was carried out on both the main land and islands of South Korea (Fig. 1). Geographically, the southern and western parts have flat plains and lowlands, but the eastern and northern parts of the country are mostly covered by hills and mountains. The climate of South Korea is typically categorized into cold temperate, temperate, and warm temperate with four distinct seasons. The southern coastal region and islands have warm temperate climates, the central and northern regions have temperate climates, and the high mountains have cold temperate climates. The average winter temperature ranges from -6°C to 3°C, and the average summer temperature ranges between 23°C and 26°C (Korea Meteorological Administration 2020). The southern region is warm and humid, and the northern region is relatively cold and dry. The annual precipitation ranged between 1,200 ~ 1500 mm, and the rate of precipitation is higher in the southern coastal region and Jeju Island than in the central and northern regions (Korea Meteorological Administration, 2020). The country is rich in biodiversity and has 5,308 plants, 1,899 vertebrates, and 22,612 invertebrates, including 15,651 insects (National Institute of Biological Resources, 2014).

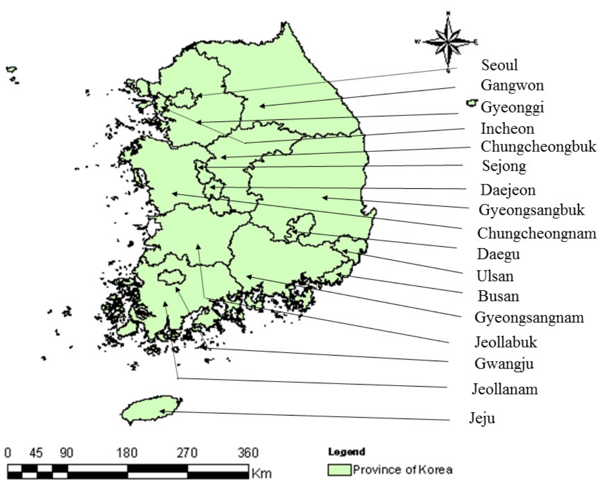

Fig. 1. Map of South Korea and different provinces

2.2 Study species

The species presence points of eight southern butterflies including spotless grass yellow (*Eurema laeta*), common grass blue (*Zizina otis*), spangle butterfly (*Papilio protenor*), constable butterfly (*Dichorragia nesimachus*), pea blue butterfly (*Lampides boeticus*), forest pierror (*Taraka hamada*), small branded swift (*Pelopidas mathias*), and common bluebottle (*Graphium sarpedon*) were obtained from our field surveys and secondary sources (Table 1 and Fig. 2) (National Institute of Environmental Research, 2013). These species are particularly distributed in the southern regions of Korea such as Jeju, Jeollanam, Gwangju, Jeollabuk, Gyreongsangnam, Busan, Ulsan, Daegu (Kim et al., 2012). Globally these species are distributed in East Asian countries such as China, Taiwan, Japan, South Korea, and Myanmar, Oriental region and Australia. These species were recorded in South Korea between 1938 and 1955 (Kwon et al., 2012).

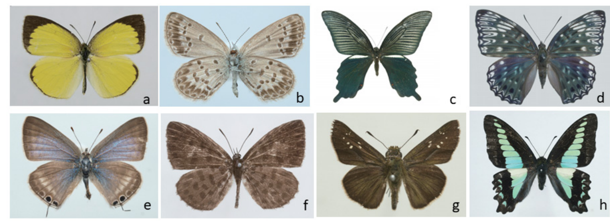

Fig. 2. Photographs of southern butterflies. a, *Eurema laeta*; b, *Zizina otis*; c, *Papilio protenor*; d, *Dichorragia nesimachus*; e, *Lampides boeticus*; f, *Taraka hamada;* g, *Pelopidas mathias*; h, *Graphium sarpedon*

(Photograph source: Kim et al., 2012)

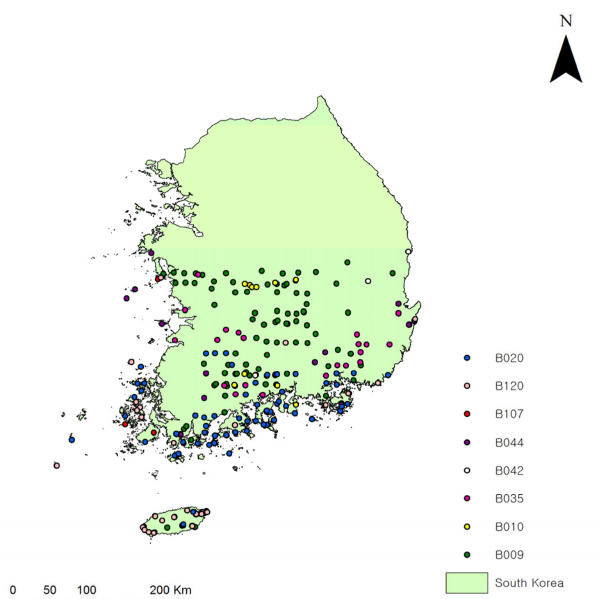

Fig. 3. Species presence points of southern butterflies. B009, *Eurema laeta*; B010, *Zizina Otis*; B020, *Papilio protenor*; B035, *Dichorragia nesimachus*; B042, *Lampides boeticus;* B044, *Taraka hamada*; B107, *Pelopidas mathias*; and B120, *Graphium sarpedon*

The main habitat of four southern butterflies *Eurema laeta*, *Zizina otis*, *Lampides boeticus*, *Taraka hamada*, *Pelopidas mathias* is grassland but remaining are found in forest edge and forest inside. The main host plants for these species are included in Table 1. At least 17 species presence points were used to model each southern butterfly in MaxEnt to obtain accurate model performance (Table 1 and Fig. 3). The duplicated points were removed, and used in the analysis.The random points were selected from the raster map of South Korea with ArcGIS 10.3 (ESRI, Redlands, CA, USA).

2.3 Environmental variables

Nineteen bioclimatic variables (Busby, 1991; Xu and Hutchinson, 2011) and altitude were considered to be important to the distribution of the southern butterfly. Climatic data, such as monthly maximum and minimum temperatures and precipitation, were obtained from the Korea Meteorological Administration to predict the current and future climate change scenarios of South Korea. We used the HedGEM3-RA global circulation model to estimate the climate change scenarios RCP 4.5 and RCP 8.5 using Package Dismo in R (Robert et al., 2020). The current climate conditions were determineby averaging the data from 1950 to 2000. The future climate conditions in 2050 and 2070 were predicted from the period of 2046 to 2055 and 2066 to 2075, respectively. The spatial resolution for each climate dataset was 0.01° (36 sec) and approximately 1 km^2. Pearson's correlation method was used to select the bioclimatic variables and removed the weaker predictors, which showed a high correlation (> 0.70) with another variable.

Table 1. Southern butterflies used in this study

Family	Species name	Common name	Korean name	Habitat	Food plant	Global distribution	Presence point	AUC value	TSS value
Pieridae	*Eurema laeta*	Spotless grass yellow	극남노랑나비	Grassland	*Cassia nomame*	East Asia, south Asia, Australia	165	0.967	0.845
Lycaenidae	*Zizina otis*	Common grass blue	극남부전나비	Grassland	*Lotus corniculatus, Trifolium repens*	Korea, China, Japan, Oriental region, Australia	25	0.904	0.780
Papilionidae	*Papilio protenor*	Spangle butterfly	남방제비나비	Forest edge	*Zanthoxylum schinfolium, Poncirus trifoliata*	Korea, China, Japan, Oriental region, Australia, Myanmar,	86	0.959	0.808
Nymphalidae	*Dichorragia nesimachus*	Constable butterfly	먹그림나비	Forest inside	*Meliosma myriantha*	Korea, China, japan, Indo-China, Himalaya	35	0.947	0.838
Lycaenidae	*Lampides boeticus*	Pea blue butterfly	물결부전나비	Grassland	*Dolichos lablab*	Oriental region	23	0.939	0.850
Lycaenidae	*Taraka hamada*	Forest pierror	바둑돌부전나비	Grassland	*Setaria viridis, Digitaria sanguinalis*	Korea, Japan, China, Oriental region, Australia	17	0.934	0.776
Hesperiidae	*Pelopidas mathias*	Small branded swift	제주꼬마팔랑나비	Grassland	*Dolichos lablab*	Oriental region	21	0.986	0.965
Papilionidae	*Graphium sarpedon*	Common bluebottle	청띠제비나비	Forest inside	*Machilus thunbergii, Cinnamomum camphora*	Korea, Japan, China, Oriental region, Australia	90	0.987	0.940

2.4 Ecological modeling, evaluation and validation

MaxEnt Package 1.3.3 for R (https://cran.r-project.org/src/contrib/Archive/maxent/) was used to estimate the potential impact of climate change on the eight species of the southern butterfly of Korea (Table 1) under current and future climate change scenarios. The data were randomly split; 75% of the data were used in the model calibration, and 25% of the data were used in the model validation. The model was replicated 10 times, and the other parameters used default settings. The accuracy of the model was examined, and validation was performed using both the area under the receiver-operating characteristics curve (AUC) (Pearsons 2010) and the true skill statistic (TSS) (Allouche et al., 2006). The AUC value ranges between 0 and 1 and acts as a threshold-independent approach to recognizepresence from absence to evaluate model performance (Thuiller et al., 2005). The model performance was assorted as excellent (0.9 ~ 1), very good (0.8 ~ 0.9), good (0.7 ~ 0.8), fair (0.6 ~ 0.7), and failed (< 0.5) (Swets, 1988). The TSS value accounts for both sensitivity and specificity and ranges between -1 and 1, determining both commission and omission errors (Allouche et al., 2006; Lobo et al., 2008). The values towards 1 indicate an agreement between the observation and prediction, and the value towards -1 indicates an agreement no better than random (Allouche et al., 2006). Similarly, the jackknife test was performed in each species to evaluate the importance of each variable in the model performance.

2.5 Prediction of potential habitat, species richness and habitat expansion

The area of suitable habitat for each southern butterfly was estimated under the climate change scenarios RCP 4.5 and 8.5 for 2030, 2050, and 2080. To determine the species richness map, we combined the binary maps representing the distribution of each butterfly under the current and future climate change scenarios as like to Saarimaa et al. (2019). A shape file of 17 provinces in Korea was overlaid on the species richness map, and the average and maximum species richness of butterflies were extracted for each province using the zonal statistics of the spatial analyst tool in ArcGIS 10.3 (ESRI, Redlands, CA, USA) as like to (Adhikari et al., 2018; 2019).

The expansion of southern butterflies was determined by differentiating between the current and future distribution habitats of each butterfly and reclassifying thembased on the potential expansion of new habitats compared to the current habitats. The habitat expansions of each species were overlaid, and the potential expansion map of southern butterflies in different provinces of South Korea was determined. The overall process was conducted with R software (https://www.r-project.org).

3. Results

3.1 Selection of bioclimatic variables and contribution to the model

Pearson's correlation test was performed to select the bioclimatic variables from the 19 bioclimatic variables and the annual mean temperature (Bio1), mean diurnal temperature range (Bio2), isothermality (Bio3), annual precipitation (Bio12), precipitation of the wettest month (Bio13), and precipitation of the driest month (Bio14) were selected (Table 2). These bioclimatic variables had weak correlations with each other but strongly correlated ($r < 0.99$) with other variables, e.g., Bio4, Bio5, and Bio7. The threshold for a weak correlation was $r < 0.5$. The selected bioclimatic variables and altitude were used in the MaxEnt model to understand the current and future distributions of southern butterflies.

Table 2. List of bioclimatic variables

Code	Description	Unit	Source
Bio1	**Annual mean temperature**	**Degrees Celsius**	**KMA**
Bio2	**Mean diurnal temperature range**	**Degrees Celsius**	**KMA**
Bio3	**Isothermality (BIO2/BIO7) (* 100)**	**Degrees Celsius**	**KMA**
Bio4	Temperature seasonality	Degrees Celsius	KMA
Bio5	Max temperature of warmest month	Degrees Celsius	KMA
Bio6	Min temperature of coldest month	Degrees Celsius	KMA
Bio7	Temperature annual range	Degrees Celsius	KMA
Bio8	Mean temperature of wettest quarter	Degrees Celsius	KMA
Bio9	Mean temperature of driest quarter	Degrees Celsius	KMA
Bio10	Mean temperature of warmest quarter	Degrees Celsius	KMA
Bio11	Mean temperature of coldest quarter	Degrees Celsius	KMA
Bio12	**Annual precipitation**	**Millimeters**	**KMA**
Bio13	**Precipitation of wettest month**	**Millimeters**	**KMA**
Bio14	**Precipitation of driest month**	**Millimeters**	**KMA**
Bio15	Precipitation seasonality	Fraction	KMA
Bio16	Precipitation of wettest quarter	Millimeters	KMA
Bio17	Precipitation of driest quarter	Millimeters	KMA
Bio18	Precipitation of warmest quarter	Millimeters	KMA
Bio19	Precipitation of coldest quarter	Millimeters	KMA

KMA = Korea Meteorological Administration

The variables with the highest model contributions differed among the species (Table 3). Of the variables, Bio 2 contributed the most (73.40 ~ 88.86%) to the modeling of four butterflies, *Papilio protenor*, (*Lampides boeticus*), and *Graphium sarpedon*. Bio1 contributed the most to *Dichorragia nesimachus* (37.63%) and *Taraka hamada* (68.50%). Similarly, Bio12 contributed the most to *Eurema laeta* (40.48%) and *Parantica sita* (45.09%). Interestingly, two butterflies, *Zizina otis* and *Choaspes benjamini*, contributed the most to altitude in the model, contributing 37.90% and 35.19%, respectively. The temperature-related variable mean diurnal temperature range was the dominant driving factor for the species distributions of the many southern butterflies.

Table 3. Contribution (%) of bioclimatic variables in the model

Species name	Bio01	Bio02	Bio03	Bio12	Bio13	Bio14	Altitude
Eurema laeta	27.45	2.81	5.14	40.48	15.19	1.77	7.16
Zizina otis	27.83	0.00	7.93	0.00	4.14	22.21	37.90
Papilio protenor	12.01	69.09	1.94	4.80	0.86	5.89	5.42
Dichorragia nesimachus	37.63	32.11	0.74	3.41	0.39	6.59	19.13
Lampides boeticus	0.00	88.86	0.83	0.00	5.34	0.02	4.95
Taraka hamada	68.50	9.43	1.02	0.97	14.41	0.19	5.49
Pelopidas mathias	1.06	36.49	0.00	45.09	0.62	5.09	11.64
Graphium sarpedon	21.16	73.40	1.16	0.00	0.00	3.17	1.12

3.2 Evaluation and validation of the model

An independent model was established for all the butterflies used in this study for predicting the current and future distribution. Two model evaluation methods were used for the predictions. Overall, 8 species of southern butterflies were used in this study (Table 1), and an independent species distribution model was determined to estimate the current and future distributions of each butterfly. We used the AUC and TSS values to assess the predictive ability of the model (Table 1). The AUC values ranged between 0.904 and 0.987 (mean 0.952), and the TSS values ranged between 0.780 and 0.965 (mean 0.850). Based on the AUC values, all the species showed excellent model performance, and the values of TSS revealed perfect agreement between the observations and predictions.

3.3 Estimation of suitable habitats

The extents of suitable habitats for the eight species of southern butterflies were modeled to show the distribution of each butterfly, and the calculated areas of suitable habitats under the current and future climate change scenarios are shown in Table 4. Out of the eight southern butterflies, *Zizina otis* had the highest suitable area (27,462 km^2) under current climatic conditions, and *Pelopidas mathias* had the least area of suitable habitat (3,072 km^2). *Lampides boeticus* and *Taraka hamada* were second and third, respectively, in terms of the distribution of suitable habitats (Table 4). Similarly, *Lampides boeticus* will have the highest suitable area in the future, which will continue to be the case in 2030, 2050, and 2080 under both the climate change scenarios RCP 4.5 and RCP 8.5 (Table 4).

Table 4. Potential habitat (km^2) of southern butterfly under the current and future climate change

Species name	Current	RCP 4.5			RCP 8.5		
		2030	2050	2080	2030	2050	2080
Eurema laeta	11,900	28,095	49,681	67,831	36,911	37,414	54,837
Zizina otis	27,462	51,202	61,396	71,040	46,591	50,580	52,665
Papilio protenor	8,964	11,564	17,999	25,293	12,503	8,440	11,134
Dichorragia nesimachus	16,531	21,912	51,817	57,901	32,888	35,759	23,553
Lampides boeticus	21,494	42,607	76,016	87,517	53,511	78,870	95,145
Taraka hamada	21,353	34,828	45,994	28,126	23,132	54,346	43,241
Pelopidas mathias	3,072	7,073	8,918	14,227	7,366	10,423	30,043
Graphium sarpedon	3,953	4,820	3,228	1,536	4,287	1,685	409

We calculated the area of new habitat expansion for each butterfly separately, which showed that the expansion of suitable habitat will be greatest by 2030 (27,561 km^2) for *Zizina otis*, and by 2050 (53,890 km^2) and 2080 (65,293 km^2), the *Lampides boeticus* will have the greatest habitat expansion under RCP 4.5 (Table 5). Under RCP 8.5, *Lampides boeticus* will have the highest habitat expansions by 2030, 2050, and 2080, which are projected to be 31,568, 56,778, and 72,877, respectively. Based on the model predictions, the areas of suitable habitat and species richness of the southern butterflies are expected to increase in provinces in the northern regions (＞36°N latitude), such as Chungcheongbuk, Gyeonggi, Gangwon, Incheon, and Seoul. In comparison to the current rate of habitat expansion, those by 2030, 2050, and 2080 are projected to be 51.07 ~ 209.26%, 74.23 ~ 264.15%, and 62.32 ~ 858.95%, respectively.

Table 5. Potential habitat expansion (km^2) of southern butterfly under the future climate change

Species name	Current	RCP 4.5			RCP 8.5		
		2030	2050	2080	2030	2050	2080
Eurema laeta	11,900	16,251	38,123	57,868	24,902	27,104	50,124
Zizina otis	27,462	27,561	35,952	48,143	26,918	27,574	42,144
Papilio protenor	8,964	7,086	13,374	22,523	8,351	6,654	11,029
Dichorragia nesimachus	16,531	8,644	36,578	43,869	19,326	21,951	22,903
Lampides boeticus	21,494	20,675	53,890	65,293	31,568	56,778	72,877
Taraka hamada	21,353	18,055	29,727	13,309	10,907	36,155	30,684
Pelopidas mathias	3,072	3,797	5,557	10,690	4,107	6,989	26,387
Graphium sarpedon	3,953	2,192	1,818	1,144	1,882	842	379

3.4 Current species richness of southern butterflies

The potential species richness of southern butterflies under the current climate is presented in Fig. 4 and Table 6. The provinces located in the southern region of Korea (below 36° latitude), including Jeju, Jeollanam, Busan, Ulsan, Gyeongsangnam and Gwangju, showed pronounced species richness that is predicted to have an average species richness of 2.96 ~ 5.83 and a maximum species richness of 7~8. However, the provinces of the central and northern regions of Korea (above 36° latitude), such as Chungcheongnam, Daejeon, Gyeonggi, Gangwon, Incheon and Seoul, showed relatively low species richness, with the average species richness ranging from 0.02 to 1.27, with maximum species richness predicted to range between 2 and 6.

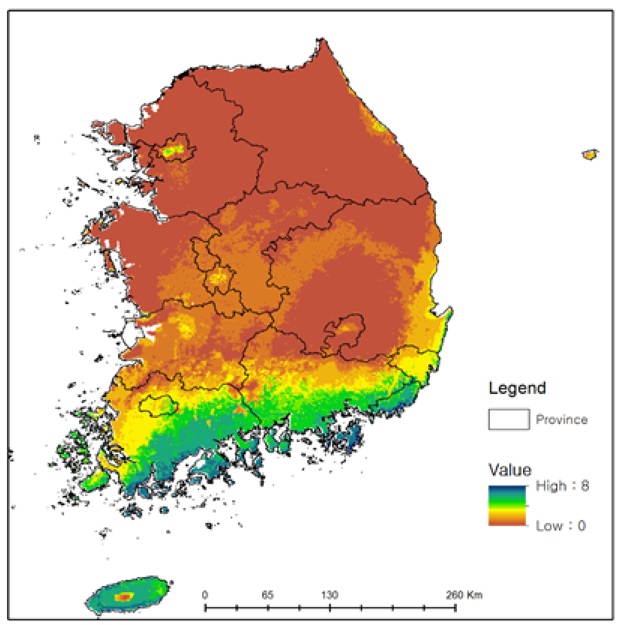

Fig. 4. Species richness of southern butterflies under the current climate

3.5 Potential species richness of southern butterflies

The potential species richness of the southern butterfly was predicted to increase in the northern regions of South Korea, particularly in Gyeongsangbuk Province, Daegu Province, Chungcheongnam Province, Gyeonggi Province, Gangwon Province, Incheon Province, and Seoul Province, by 2030, 2050, and 2080 under the climate change scenarios RCP 4.5 and RCP 8.5 (Fig. 5 and Table 5). The rates of increase in the average species richness were predicted to be inconsistent in different provinces. In comparison to the southern regions, the northern regions of South Korea were predicted to have relatively high increase rates for average species richness in the future, where species richness was estimated to increase 52.07 ~ 1318% by 2030, 207 ~ 5,415.97% by 2050, and 237.936 ~ 17,727.27% by 2080 under RCP 4.5 compared the increases in the current richness.

This indicates that habitat expansion of southern butterflies will likely be rapid in the northward direction in the future. However, two provinces located in the southern region of South Korea (Jeju and Busan) will likely have a decreasing trend in average species richness, which was predicted to be 33.54%, 96.22%, and 53.90% by 2030, 2050, and 2080, respectively.

The maximum species richness of southern butterflies was not estimated to increase as much as the average species richness in both the southern and northern regions. The maximum species richness values in Jeollabuk, Daegu, Daejon, Chungcheongbuk, Gyeongsangbuk, Gyeonggi, Gangwon, Incheon, and Seoul Provinces were predicted to be 2 ~ 7 by 2030 and 5-8 by 2050 and 2080 (Table 5).

3.6 Potential species expansion of southern butterflies

The potential species expansions of southern butterflies in different provinces of South Korea are presented in Fig. 6 and Table 7. Similar to species richness, species expansion will likely be relatively high in the provinces in the northern region, e.g., Daegu, Chungcheongnam, Gyeonggi, Gangwon, Incheon, and Seoul, compared to that in the southern region. The average species expansion was estimated to be highest in Daegu Province by 2030, Chungcheongnam Province by 2050, and Gyeonggi Province by 2080 under the climate change scenario RCP 8.5. Similarly, the maximum species expansion of southern butterflies will likely be highest in Gangwon Province (8 species) by 2030, 2050, and 2080. These results indicate a northward habitat shift in southern butterflies due to climate change.

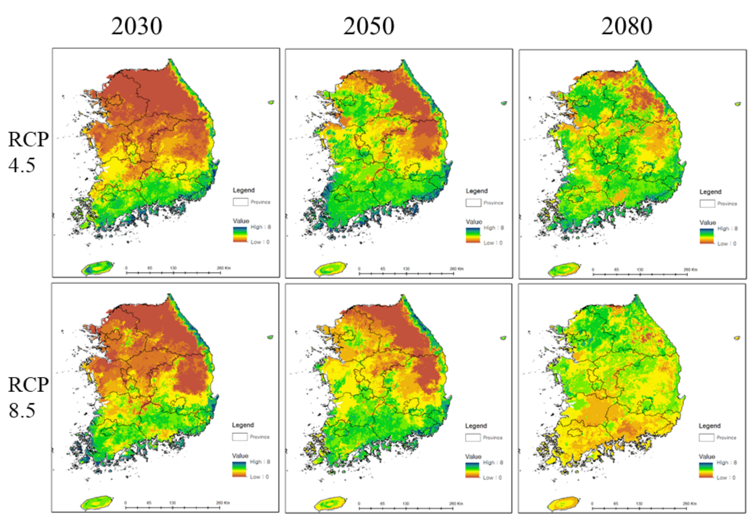

Fig. 5. Potential species richness of southern butterflies under the climate change scenarios RCP 4.5 and RCP 8.5.

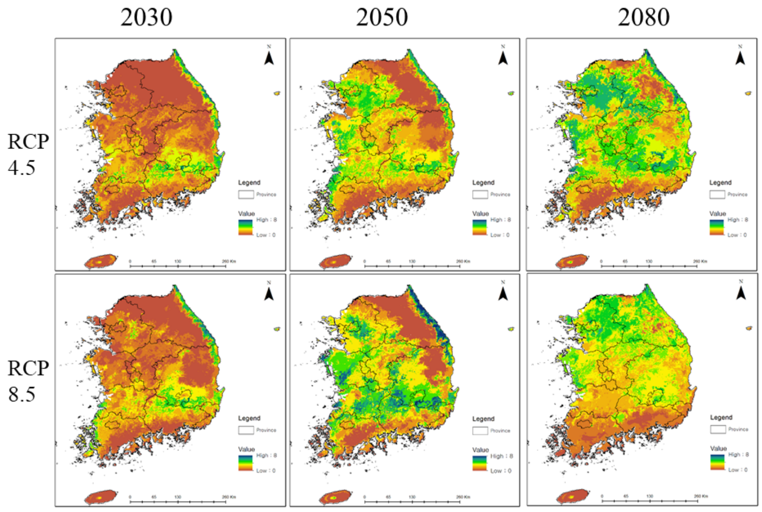

Fig. 6. Potential habitat expansion of southern butterflies under the climate change scenarios RCP 4.5 and RCP 8.5

Table 6. Average and maximum species richness of southern butterfly in different provinces of Korea

Province name	Current		RCP 4.5						RCP 8.5					
			2030		2050		2080		2030		2050		2080	
	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
Seoul	0.84	5.00	0.89	2.00	4.25	6.00	4.50	7.00	3.50	4.00	2.71	5.00	3.99	6.00
Incheon	0.06	3.00	0.68	3.00	3.25	5.00	2.80	6.00	2.80	3.00	2.05	4.00	3.90	7.00
Gangwon	0.04	5.00	0.57	6.00	1.50	8.00	2.72	7.00	2.72	8.00	1.22	8.00	3.60	8.00
Gyeonggi	0.02	2.00	0.29	5.00	3.23	6.00	3.84	6.00	3.84	5.00	2.14	6.00	3.98	6.00
Sejong	0.83	1.00	1.26	3.00	2.54	3.00	3.19	5.00	3.19	3.00	2.11	3.00	3.01	4.00
Chungcheongbuk	0.44	1.00	0.95	3.00	2.76	6.00	3.70	5.00	3.70	4.00	1.92	5.00	3.35	5.00
Daejeon	1.27	4.00	2.83	5.00	4.06	6.00	4.28	5.00	4.28	6.00	2.47	5.00	3.57	5.00
Chungcheongnam	0.32	5.00	1.53	5.00	3.66	6.00	3.67	7.00	3.67	5.00	2.92	6.00	3.55	7.00
Daegu	0.26	2.00	3.01	6.00	3.33	6.00	3.76	6.00	3.76	6.00	2.95	6.00	3.66	6.00
Jeollabuk	1.02	4.00	2.59	7.00	4.18	8.00	3.88	7.00	3.88	7.00	2.85	7.00	2.57	5.00
Gyeongsangbuk	0.49	6.00	1.92	8.00	2.48	8.00	3.44	8.00	3.44	8.00	2.07	6.00	3.31	6.00
Gwangju	3.16	6.00	4.03	6.00	4.79	7.00	4.14	6.00	4.14	6.00	1.38	5.00	2.79	4.00
Ulsan	2.92	7.00	5.37	8.00	5.31	8.00	4.83	7.00	4.83	8.00	2.16	5.00	3.14	5.00
Busan	5.83	8.00	5.67	8.00	6.49	8.00	5.13	7.00	5.13	7.00	1.27	4.00	2.69	3.00
Gyeongsangnam	2.96	8.00	4.37	8.00	4.67	8.00	4.38	8.00	4.38	7.00	2.03	6.00	2.40	6.00
Jeollanam	4.26	8.00	4.51	8.00	5.20	8.00	4.45	8.00	4.45	8.00	1.20	6.00	2.70	6.00
Jeju	5.65	7.00	4.58	8.00	3.60	6.00	3.62	6.00	3.62	5.00	0.21	3.00	2.61	4.00

Avg: average species richness; Max: maximum species richness

4. Discussion

Globally, climate change is an important factor for distribution, range shifts, and habitat expansions of flora and fauna including butterfly species (Kappelle et al., 1999). Our model estimated that all southern butterflies, except *Graphium Sarpedon*, will retain their current distributions with additional habitat expansions, as noted in (Kwon et al., 2014). However, the rates and extents of suitable habitats were different for each species. Four species, *Eurema laeta, Zizina otis*, *Lampides* *boeticus*, and *Pelopidas mathias,* were predicted to have relatively high rates of habitat expansion (Table 5), estimated at 96.18～209.26% by 2030, 180.89～320.36% by 2050, and 303.73.77～858.95% by 2080 in comparison to the rates in current climatically suitable habitat. The expansion of suitable habitats of southern species depends on not only climatic variables such as temperature and precipitation applied in the MaxEnt model but also habitat types, land cover change, and life history traits such as food plant types, overwintering stage, and voltinism (Kwon et al., 2013; Kwon et al., 2014).

Habitat type could be another important factor for the potential distribution of butterflies. In this study, we determined that the rate of habitat expansion will be higher for grassland species, e.g., *Eurema laeta*, and *Pelopidas mathias,* than for forest species. Therefore, the climatically suitable habitat for each butterfly could be distinct under the same climatic conditions in the future. Climate change may limit the distribution of several insect communities, including aquatic insects (Li et al., 2014). We predict a decrease in the suitable habitat for *Graphium sarpedon* under both climate change scenarios (Table 4). Temperature-related variables (Bio1 and Bio2) have contributed substantially in the model, indicating that an increase in temperature is not favorable to butterfly life cycle, potentially affecting the physiology of eggs and metamorphosis (Potter et al., 2009; Klockmann et al., 2017).

Climate change induces habitat expansion of biodiversity poleward and uphill across the globe (Menéndez et al., 2014; Pecl et al., 2017; Shamsabad, 2018; Lee et al., 2020). In this study, we also predicted that the northern margin of the southern butterfly shifted to the north, leading to habitat expansion of southern butterflies towards the central and northern regions. It is widely known that in comparison to northern regions, southern regions (lower latitudes) have higher habitat temperatures, so southern butterflies are considered warm-adapted species; however, due to their low limits of thermal tolerance, they are likely to expand their territories towards the north (Vanhanen et al., 2007; Montejo-Kovacevich et al., 2020; Lee et al., 2020). Earlier studies in Korea and abroad have revealed that with temperatures higher than 37°C, species in southern communities tended to move slowly northward (Parmesan, 1996; Warren et al., 2001; Forister et al., 2010; Kwon et al., 2014; Lee et al., 2020), which indicates that increasing temperature could be an important component affecting habitat shifts.

Here, we show the northward range expansion of southern butterflies that are predicted to increase in species richness in the northern region, particularly in Gyeongsangbuk Province, Chungcheongnam Province, Gyeonggi Province, Incheon Province, Gangwon Province, and Seoul Province, as noted in (Choi, 2004). Although we did not calculate the northern margin shift of southern butterflies, earlier studies revealed an average of 1.6 km per year in South Korea (Kwon et al., 2014), 1.8 km per year in the UK (Hickling et al., 2006), and 3.4 km per year in North America (Crozier, 2004). Lee et al. (2020) reported that both northern and southern butterflies are sensitive to climate change, but in comparison to northern butterflies, southern butterflies show greater habitat shifts.

Climate change can affect flight times in insect communities, including butterflies. Warmer temperatures may result in the production of many generations of multiple-brooded species, but how temperature affects egg laying and other biological traits determined by photoperiod is still not well studied (Polgar et al., 2013). Therefore, further studies are required to understand the physiological effects of warmer climates on butterflies. However, our study showed the general pattern of southern butterflies expanding their territory to the northern region.

Butterflies are severely dependent on plants for nectar and larval hosts, so the phenology of butterflies strongly depends on the phenology of their host plants (Navarro-Cano et al., 2015). Climate change affects not only animal species but also plant species. Earlier studies revealed a range shift, habitat expansion or reduction in plant species in response to climate change in Korea and other countries (Frei et al., 2010; Adhikari et al., 2018, 2019; Shin et al., 2018; Jeon et al., 2020; Zhang, 2020). Seo et al. (2017) showed habitat expansion of *Meliosma myriantha* (southern plant) and habitat reduction of *Machilus thunbergii* (sensitive species) under future climate change in Korea, which are the principle host plants of the two southern butterflies *Dichorragia nesimachus*, and *Graphium sarpedon*, respectively. These results indicate that habitat expansion or reduction in southern

Table 7. Average and maximum species expansion of southern butterfly in different provinces

Province name	RCP 4.5						RCP 8.5					
	2030		2050		2080		2030		2050		2080	
	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
Seoul	0.70	2.00	3.46	6.00	3.87	7.00	0.86	4.00	2.71	5.00	3.63	6.00
Incheon	0.59	2.00	3.28	5.00	2.86	6.00	0.45	2.00	2.05	4.00	3.93	7.00
Gangwon	0.54	6.00	1.46	8.00	2.69	7.00	0.84	8.00	1.22	8.00	3.59	8.00
Gyeonggi	0.29	5.00	3.22	6.00	3.83	6.00	0.86	5.00	2.14	6.00	3.98	6.00
Sejong	0.89	3.00	1.82	3.00	2.36	4.00	0.57	3.00	2.11	3.00	2.18	4.00
Chungcheongbuk	0.58	3.00	2.32	5.00	3.26	5.00	0.82	3.00	1.92	5.00	3.00	5.00
Daejeon	1.68	4.00	2.89	6.00	3.05	5.00	1.42	5.00	2.47	5.00	2.48	5.00
Chungcheongnam	1.23	4.00	3.35	6.00	3.37	7.00	1.10	5.00	2.98	6.00	3.30	7.00
Daegu	2.75	6.00	3.07	6.00	3.50	6.00	3.26	6.00	2.95	6.00	3.40	6.00
Jeollabuk	1.68	7.00	3.19	8.00	3.02	7.00	2.17	7.00	2.85	7.00	2.07	5.00
Gyeongsangbuk	1.52	7.00	2.09	6.00	3.04	6.00	1.75	6.00	2.07	6.00	2.92	6.00
Gwangju	1.10	5.00	1.88	4.00	1.53	4.00	1.67	3.00	1.38	5.00	1.06	4.00
Ulsan	2.64	5.00	2.54	5.00	2.43	5.00	2.37	5.00	2.16	5.00	1.58	5.00
Busan	1.38	5.00	1.31	5.00	1.20	4.00	1.15	5.00	1.27	4.00	0.84	2.00
Gyeongsangnam	1.84	6.00	2.14	6.00	2.14	6.00	1.83	6.00	2.03	6.00	1.37	6.00
Jeollanam	0.92	5.00	1.58	8.00	1.23	7.00	1.37	7.00	1.20	6.00	1.01	5.00
Jeju	0.36	4.00	0.18	3.00	0.36	4.00	0.11	3.00	0.21	3.00	0.15	4.00

Avg: average species richness; Max: maximum species richness

butterflies is strongly correlated with the impact of climate change on their principle host plants.

The habitat expansion of southern butterflies to the north may cause overlapping ranges among northern and southern species, which could create competition for habitats and resources with northern species, and this scenario could be a threatening factor for both types of butterflies. In addition, disease, human activities, and their impacts such as habitat loss and fragmentation, use of pesticides and herbicides in crops, and industrial pollution can lead to declining populations and local extinction (Preston et al., 2012; Pleasants and Oberhauser, 2013).

5. Conclusions

In this study, we predicted the suitable habitats of southern butterflies under current and future climate change in South Korea using a species distribution model (MaxEnt). Our study revealed that the habitat of southern butterflies is currently limited to the southern region of South Korea, but their northern habitat range will expand continuously in the future and be distributed in the northern limit of South Korea by 2080. In this study, our model was based only on bioclimatic variables excluding other important variables such as land use and land cover change, biotic interactions including competition with northern butterfly species, and pollution. Thisstudy is part of ongoing research; therefore, in our next study, we will consider using other nonclimatic variables to obtain more accurate predictions in the near future. This study provides valuable information about the current and future distributions of southern butterflies, which could be important information for the government and conservation agencies to use in developing conservation strategies for southern butterflies.

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