Eco. Env. & Cons. 26 (August Suppl. Issue) : 2020; pp. (S145-S155)
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ISSN 0971–765X

Impact of climate change on potential dispersal of *Paeonia obovata* (paeoniaceae), a critically endangered medicinal plant of South Korea

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(Received 6 February, 2020; accepted 13 March, 2020)

ABSTRACT

In recent years, global climate change has been considered a major threat to biodiversity, particularly to high-elevation plants. *Paeonia obovata* is a critically endangered medicinal plant that occurs at high altitudes and latitudes. In this study, the maximum entropy (MaxEnt) and Mig Clim models were used to predict the potential dispersal of *P. obovata* in South Korea in relation to current and future climate change scenarios representative concentration pathways (RCP) 4.5 and RCP 8.5. Based on the model predictions, the current suitable habitat of *P. obovata* is approximately 15,397 km^2 and is estimated to decline substantially by as much as 67.86%, 84.90%, and 98.63% by 2030, 2050, and 2080, respectively, under a dispersal limitation of 10 km/year. The model simulations indicated that the suitable habitat of *P. obovata* would significantly decrease and would almost disappear after 2080. Based on our findings, we urge implementation of the necessary conservation activities, including *insitu* and *exsitu* conservation, particularly focusing on northern and northern eastern regions of the country.

Key words : *Climate change, MaxEnt, MigClim, Plant dispersal, Paeonia obovata*

Introduction

Paeonia obovata is a perennial herbaceous peony plant (Paeoniaceae) native to Korea, Japan, China, Siberia, and Manchuria. It predominantly grows in the wild, mostly at high altitudes and high latitudes. In addition to its aesthetic value, it has been regarded as an expensive traditional medicine with potent tonic activity used to treat gastric ulcers (Lee *et al.*, 1985; Bae *et al.*, 2015). Because of its medicinal value, the demand for *P. obovata* continues to grow in the markets of East Asian countries, e.g., South Korea, Japan and China. However, limited cultivation practices and over-exploitation of natural resources have resulted in a reduction of its natural habitat, similar to that of other *Paeonia* spp. (Hong *et al.*, 2017; Zhang *et al.*, 2019).

Anthropogenic activities, such as the burning of fossil fuels and deforestation, are the main cause of greenhouse gas emissions, which are responsible for climate change. According to the 5th Intergovernmental Panel on Climate Change (IPCC) report, the global climate has experienced a temperature increase of 0.78 °C throughout the 20th century, and the temperature is predicted to rise by 2.6 to 4.8 °C by 2100 (IPCC, 2013). The rate of temperature increase has varied across the world. In South Korea, the temperature has increased by 1.8 °C over the last 100 years, and it is estimated to increase by 0.63 °C by the end of this century (Ministry of Environment 2019).

Climate serves as an important factor related to plant phenology, vegetation pattern, structure, and geographical distribution (Lawler *et al.,* 2009; Walck *et al.,* 2011). Usually, high altitude plant species are sensitive to climate change, and global warming might result in a reduction in their natural habitat (Dirnbock *et al.,* 2011; Dullinger *et al.,* 2012; Adhikari *et al.,* 2018; Zhao *et al.,* 2018). Moreover, climate change has reduced habitatsat lower elevations and expanded distribution rangesat higher elevations (Zhang *et al.,* 2018; Peng *et al.,* 2019). *Paeonia* spp. require a critical chilling period to release dormancy and to restart sprouting, growing, and flowering in spring (Aoki and Yoshino, 1989; Barzilay *et al.,* 2002; Halevy *et al.,* 2005). Therefore, an increased global temperature will affect their life cycles. The integrative effects of climate change and anthropogenic pressure threaten the conservation of *P. obovata*. In South Korea, this species has been assessed as a critically endangered plant species (National Institute of Biological Resources, 2014).

Various ecological niche modeling (ENM) methods, including statistical, machine learning, and ensemble methods, are currently used in practice for modeling species distributions (Koo *et al.,* 2015; Shin *et al.,* 2018; Zhang *et al.,* 2019). Among these methods, the machine learning method maximum entropy (MaxEnt) has a higher predictive accuracy for species distribution when using a small amount of species occurrence data and environmental variables (Phillips *et al.,* 2006; Lamsal *et al.,* 2018; Shrestha and Shrestha 2019). Many ENMsignore dispersal limitations, assuming dispersal is either unlimited or null. These assumptions could be inaccurate and lead to incorrect estimations of species distributions when considering dispersal capabilities of species, rate of climate change, and habitat fragmentation (Engler and Guisan, 2009). As a result, there could be inaccurate predictions of potentially suitable and potentially colonizable habitats. To address these problems, the MigClim model, which can integrate the results obtained from Max Ent modeling and utilize the habitat suitability map as suggested by Engler *et al.* (2012), has been used to simulate the dispersal of plant species under climate change conditions and landscape fragmentation.

Although many studies have focused on the ecology, taxonomy and physiology of *Paeonia* spp. and the impact of climate change on species distributions of *Paeonia* spp. (e.g., *P. delavayi*, *P. ostia*, *P. lactiflora*, *P.rockii*, and *P. veitchii*), most studies were mostly carried in China (Evans *et al.,* 1990; Hong and Pan 1999; Halevy *et al.,* 2005; Philip *et al.,* 2011; Hong *et al.,* 2017; Zhang *et al.,* 2018, 2019; Peng *et al.,* 2019). In South Korea, very few studies have been carried out on *P. obovata* to describe its distributional characteristics, population dynamics, and biological activity (Yeo *et al.,* 2012; Bae *et al.,* 2015 and Kim *et al.,* 2016). However, the potential impacts of climate change on *P. obovata* have not yet been studied. Without adequate ecological and biological information, it is impossible to design conservation strategies (Hong *et al.,* 2017). Therefore, we aimed to estimate the current distribution and future potential dispersal of *P. obovata* under climate change conditions in South Korea to develop a theoretical reference framework for conservation strategies for this critically endangered species.

Methods

Study area

This study was conducted on both the main land and islands of South Korea (Figure 1). The northern and eastern parts of the country are mostly covered by mountains and hills, but the southern and western parts have lowlands and flat plains. The climate of South Korea is categorized as warm-temperate, temperate, and cold temperate. The northern and central parts of South Korea experience temperate climates, the southern coast and islands have a warm temperate climate, and the high mountains have a cold-temperate climate. The average summer temperatureis between 20 °C and 26 °C, and the average winter temperature ranges from -5 °C to 5 °C (National Institute of Biological Resources 2014). The northern region is relatively cold and dry, whereas the southern region is warm and humid. The rainiest season in South Korea is summer, while winter is the driest season. The annual precipitation ranges between 1,200 mm and 1,700 mm. The country is rich in biodiversity and has a record of 41,483 species, including 22,612 invertebrates, 1,899 vertebrates, and 5,308 vascular plants (National Institute of Biological Resources 2014).

Species occurrence data

The species presence points of *P. obovata* were obtained from our field surveys and secondary sources (National Institute of Environmental Research 2013; Kim *et al.,* 2016). To perform MaxEnt modeling, we selected only the data with precise locality information to ensure correct geographic distribution. The duplicated points were removed, and 48 species presence points were used in this analysis (Figure 1). The random points were determined through the raster map of South Korea with ArcGIS 10.3 (Esri, Redlands, CA, USA).

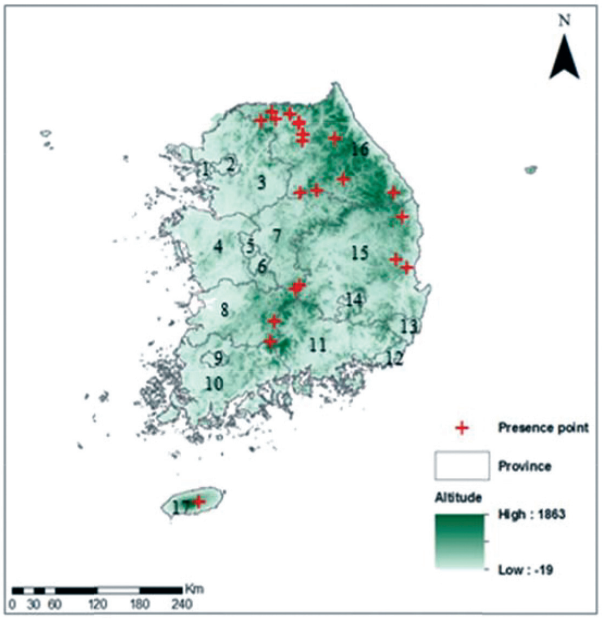

Fig. 1. Species presence points for P. *obovata*in different geographical regions of South Korea. The '+' sign indicates a species presence point. Numbers 1-17 indicate different provinces of South Korea. 1, Incheon; 2, Seoul; 3, Gyeonggi; 4, Chungcheongnam; 5, Sejong; 6, Daejon; 7, Chungcheonbuk; 8, Jeollabuk; 9, Gwangju; 10, Jeollanam; 11, Gyeongsangnam; 12, Busan; 13, Ulsan; 14, Daegu; 15, Gyeongsangbuk; 16, Gangwon; and 17, Jeju.

Environmental variables

Nineteen bioclimatic variables were considered to be significant for the distribution of *P. obovata*. Monthly minimum and maximum temperatures and precipitation data were obtained from the Korea Meteorological Administration to predict the current and future climate of South Korea. In this study, we selected bioclimatic variables, estimated current and future climate, and estimated future climate change scenarios, as performed in Adhikari *et al.* (2019). The spatial resolution for all climatic data was 0.01 degrees (36 seconds) and approximately 1 km^2.

Model development, evaluation and validation

We used the MaxEnt Package 1.3.3 for R (https://cran.r-project.org/web/packages/maxent) to estimate the potential distribution of *P. obovata* in South Koreaunder current and future climate conditions. During modeling, the data were randomly split at a ratio of 75:25 for model calibration and model validation. All other parameters used the default setting, and the model was replicated 10 times. Model accuracy and validation were assessed employing the area under the receiver-operating characteristics (ROC) curve (AUC) (Pearsons 2010) and the true skill statistic (TSS) (Allouche *et al.,* 2006). The AUC, with a range between 0 and 1, acts as a threshold-independent approach to differentiate presence from absence to evaluate model performance (Thuiller *et al.,* 2005). The model robustness was categorized as failed (0.5-0.6), fair (0.6-0.7), good (0.7-0.8), very good (0.8-0.9), and excellent (0.9-1) (Swets 1988). The TSS assesses both specificity and sensitivity and ranges from -1 to +1, accounting for both omission and commission errors. The values towards -1 indicate agreement no better than random, and the values towards +1 signify an agreement between the observation and prediction (Allouche *et al.,* 2006). Similarly, the jackknife test was carried out to evaluate the importance of each variable in terms of model performance.

Dispersal analysis

The results of MaxEnt (initial species distribution and prediction of habitat suitability) were applied to analyze the potential dispersal of *P. obovata*using MigClim (Engler 2009; Engler *et al.,* 2012). The degree of dispersal was estimated with probabilities based on the distance by employing a negative exponential dispersal kernel depending on the Euclidean distance (d) of every grid cell to the nearest known species location (Eq. 1) (Portnoy and Willson 1993).

$$D_\theta = e^{(\theta d)} \text{ for } \theta \{-0.005, -0.001, -0.0005\} \quad \text{.. (Eq. 1)}$$

where D_θ is the probability of dispersal by distance according to θ, θ is the gradient of the negative exponential function, and d is the dispersal distance. The coefficient value θ = 0.005, -0.001, -0.0005, indicating the seed dispersal kernel 1 km/year, 5 km/year (dispersal by animal), and 10 km/year (long distance dispersal), respectively,was applied for the dispersal simulation (Vellend *et al.,* 2003; Crossman *et al.,* 2012). The negative exponential function in the given equation indicated a higher dispersal potential score to the region, which is close to the known species locations compared to the farther away species locations (Crossman *et al.,* 2012). The other parameters used in this analysis were initial species distribution, habitat suitability map, barriers to seed dispersal, propagule production potential, long distance dispersal, dispersal steps, and number of environmental changes as recommended by Engler *et al.,* (2012). A prediction of the potential dispersal of each invasive species was estimated for the years 2030, 2050, and 2080 under climate change scenarios representative concentration pathways (RCP) 4.5 and RCP 8.5. All the output raster files were reclassified based on the cells being either occupied or unoccupied and colonized or noncolonized or decolonized in the simulation and were used to determine the suitable and unsuitable habitats of invasive species (Engler, 2012).

Results

Bioclimatic variable selection and their contribution to the model

Pearson's correlation analysis was performed among the 19 bioclimatic variables (Table 1), and six variables were selected: 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). All these variables hadweak correlations, but they had strong correlations (0.99>r) with other climatic variables, such as Bio4, Bio5, and Bio, 10 (Table 2). Therefore, these six variables were selected for the MaxEnt modeling of *P. obovata*. Our results showed that Bio1, Bio3, and Bio12 were the important variables in the simulation of *P. obovata* (Figure 2) and contributed 39.28%, 19.62%, and 19.41%, respectively. This result indicates that annual mean temperature, isothermality, and annual precipitation are three

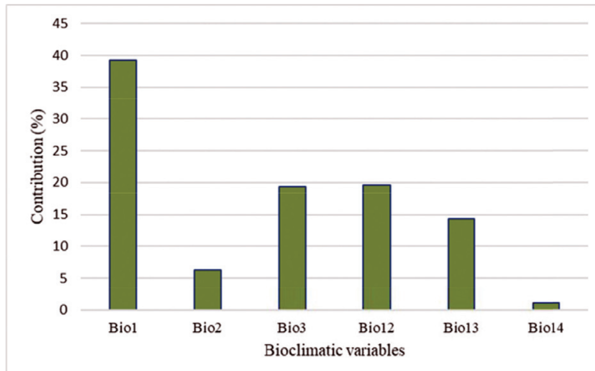

Fig. 2. Contributions of bioclimatic variables in the Max Ent model.

Table 1. 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

Table 2. Spearman's correlation for variable selection

Variable	Bio1	Bio2	Bio3	Bio4	Bio5	Bio6	Bio7	Bio8	Bio9	Bio10	Bio11	Bio12	Bio13	Bio14	Bio15	Bio16	Bio17	Bio18
Bio2	-0.52																	
Bio3	-0.02	0.61																
Bio4	-0.72	0.79	0.02															
Bio5	0.93	-0.24	0.04	-0.43														
Bio6	0.95	-0.70	-0.08	-0.89	0.79													
Bio7	-0.68	0.87	0.16	0.99	-0.39	-0.87												
Bio8	0.96	-0.34	-0.01	-0.52	0.99	0.85	-0.48											
Bio9	0.96	-0.62	-0.03	-0.85	0.84	0.99	-0.84	0.86										
Bio10	0.96	-0.36	0.00	-0.54	0.97	0.85	-0.50	0.98	0.87									
Bio11	0.96	-0.63	-0.03	-0.85	0.84	0.99	-0.82	0.89	0.99	0.89								
Bio12	0.07	-0.09	0.35	-0.35	-0.10	0.14	-0.29	-0.07	0.19	0.19	0.15							
Bio13	-0.24	0.50	0.27	0.43	-0.12	-0.38	0.48	-0.18	-0.33	-0.33	-0.32	0.57						
Bio14	0.18	-0.43	0.06	-0.58	-0.07	0.36	0.59	0.00	0.32	0.32	0.31	0.53	-0.09					
Bio15	-0.45	0.72	0.05	0.88	-0.17	-0.68	0.88	-0.26	-0.63	-0.63	-0.61	-0.16	0.67	-0.69				
Bio16	-0.18	0.32	0.37	0.13	-0.19	-0.23	0.19	-0.21	-0.16	-0.16	-0.19	0.85	0.89	0.16	0.37			
Bio17	0.34	-0.55	0.07	-0.75	0.06	0.53	-0.75	0.14	1.00	0.50	0.48	0.58	-0.16	0.95	-0.80	0.14		
Bio18	-0.24	0.41	0.40	0.24	-0.21	-0.31	0.30	-0.24	-0.25	-0.25	-0.26	0.79	0.97	0.12	0.45	0.98	0.07	
Bio19	0.27	-0.54	0.06	-0.72	-0.01	0.47	-0.72	0.07	0.45	0.45	0.42	0.60	-0.14	0.95	-0.78	0.16	0.98	0.10

major driving factors for the distribution of *P. obovata*. The other variables play minor roles for the distribution of this species.

Model evaluation and validation

The model performance was evaluated using AUC and TSS values, which were 0.934 and 0.828, respectively. The AUC indicated that the overall performance of the model was excellent; thus, it led to outstanding prediction for *P. obovata.* Similarly, the TSS valuesignified that there was an agreement between the observation and prediction of the model.

Prediction of current potential habitat

The potential habitat for *P. obovata* under current climateconditions is presented in Figure 3. The MaxEnt ecological model results showed that the highly suitable habitat regions for *P. obovata* are primarily located in northern and northeastern South Korea. Four provinces, namely, Gangwon, Seoul, Incheon, and Gyeonggi, occur in these regions. The suitable habitat of *P. obovata* in these regions is approximately 15,397 km^2, which accounts for 76.90% of the total suitable habitat in South Korea.

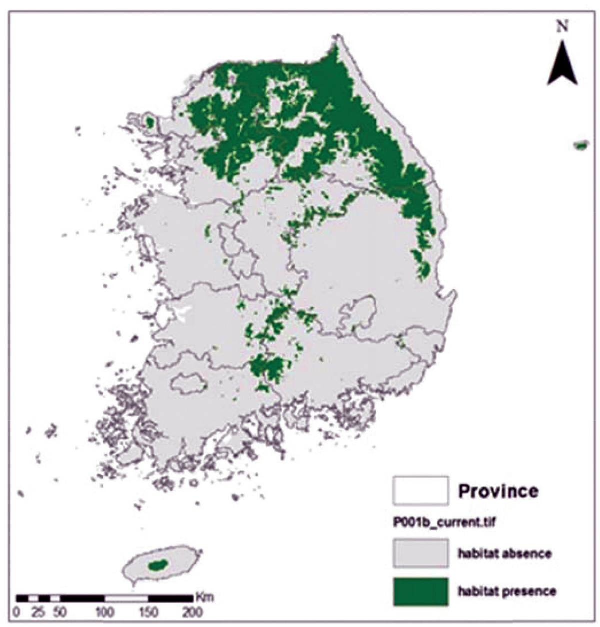

Fig. 3. Potential distribution of *P. obovata* under current climate conditions. The black lines on the map show the 17 provinces of South Korea.

Potential dispersal of *P. obovata* under future climate change conditions

The potential dispersals of *P. obovata* under the seed dispersal limitations of 1 km/year, 5 km/year, and 10 km/year and unlimited dispersal was projected for the years 2030, 2050, and 2080 under the climate change scenarios RCP 4.5 and RCP 8.5 and are expressed in Figure 4 and Figure 5, respectively. The future areas of suitable habitats of *P. obovata* were differently predicted depending on the dispersal limitations of 1 km/year, 5 km/year, and 10 km/year and unlimited dispersal (Table 3).

Under the dispersal limitation of 10 km/year, the area of suitable habitat was predicted to be 5,464 km^2, 4,397 km^2, and 961 km^2 by the years 2030, 2050, and 2080, respectively, under RCP 4.5. These results showed that the areas of suitable habitat of *P. obovata* would decline continuously by the years 2030, 2050, and 2080. The area of suitable habitat of *P. obovata* in the future was predicted to be relatively high in the northern and northeastern regions, particularly in Gangwon Province, compared to that in the central and southern regions. In the northern and northwestern regions, the area of dispersal was predicted to be 85.88-100%, 77.22-92.79%, and 74.59-93.92% higher than that in the central and southern regions under dispersal limitations of 1 km/year, 5 km/year, and 10 km/year, respectively, between 2030 and 2080.

Potential habitat loss of *P. obovata* under future climate change conditions

The potential habitat loss of *P. obovata* was simulated using seed dispersal limitations of 1 km/year, 5 km/year, and 10 km/year and unlimited dis-

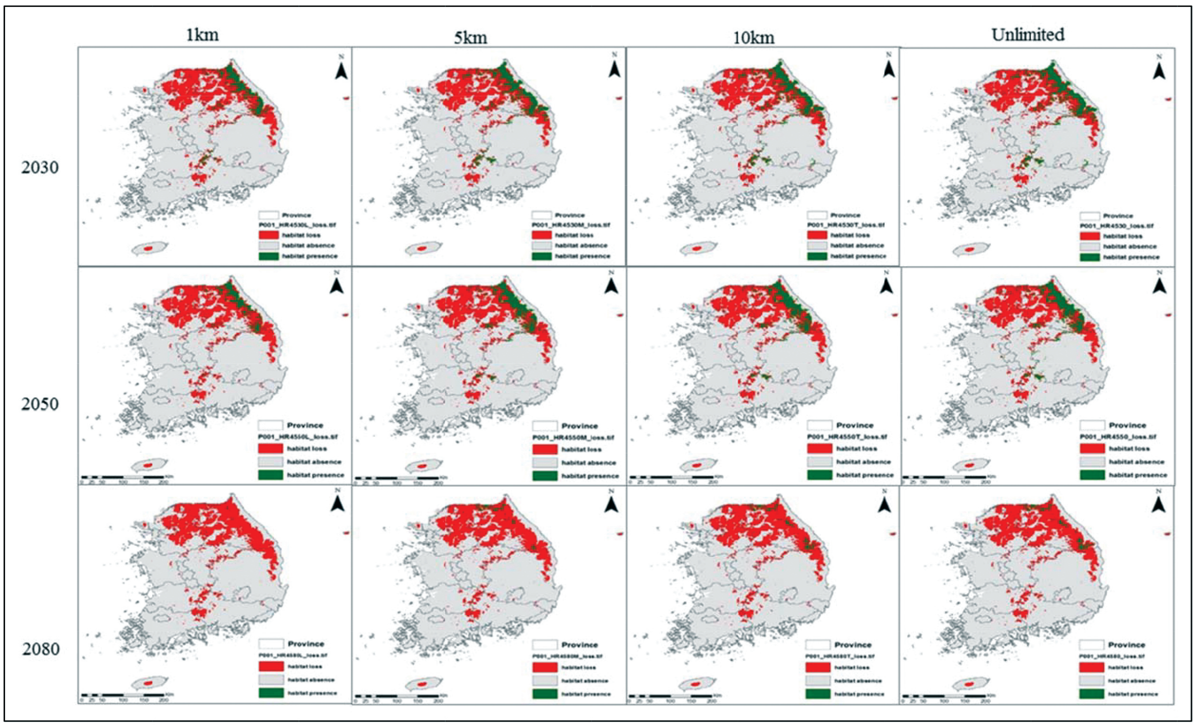

Fig. 4. Potential dispersal of *P. obovata* under climate change scenario RCP 4.5. The black lines on the map show the 17 provinces of Korea. The red, green, and gray colors on the maps indicate habitat loss, habitat presence, and habitat absence, respectively.

Table 3. Contribution of bioclimatic variables in the model

Code	Bioclimatic variable	Unit	Contribution (%)
BIO 1	Annual mean temperature	ºC	39.28
BIO 2	Mean diurnal temperature range	ºC	6.25
BIO3	Isothermality	ºC	19.41
BIO12	Annual precipitation	mm	19.62
BIO13	Precipitation of wettest month	mm	14.32
BIO14	Precipitation of driest month	mm	1.09

persal for the years 2030, 2050, and 2080 under RCP 4.5 and RCP 8.5 and is shown in Figure 4 and Figure 5, respectively. Under RCP 4.5 and RCP 8.5, our prediction shows that the rate of habitat decline is 64.51-67.86% by 2030, 71.44-84.90% by 2050, and 93.75-98.63% by 2080 under the dispersal limit of 10 km/year.

The rate of habitat loss in the southern and central regions was relatively high compared to that in the northern and northern east regions. In comparison to the current habitat of this species, the habitat loss rate in the southern and central regionswas predicted to be 76.06-83.02% by 2030, 86.46-93.05% by 2050, and 98.81-99.63% by 2080 under the dispersal limit of 10 km/year, whereas the habitat loss rate in the northern and northern east regions was predicted to be 71.70-72.95% by 2030, 75.50-86.98% by 2050, and 94.11-98.74% by 2080.

Discussion

With the changes in the Carbondioxide (CO_2) concentration, temperature, and precipitation, the variation in certain climatic resources impacts plant productivity, changing the dynamics and balance of different species (Rivaes *et al.*, 2013). When the climatic resources to which *P. obovata* are adapted change, its geographical distribution undergoes cor-

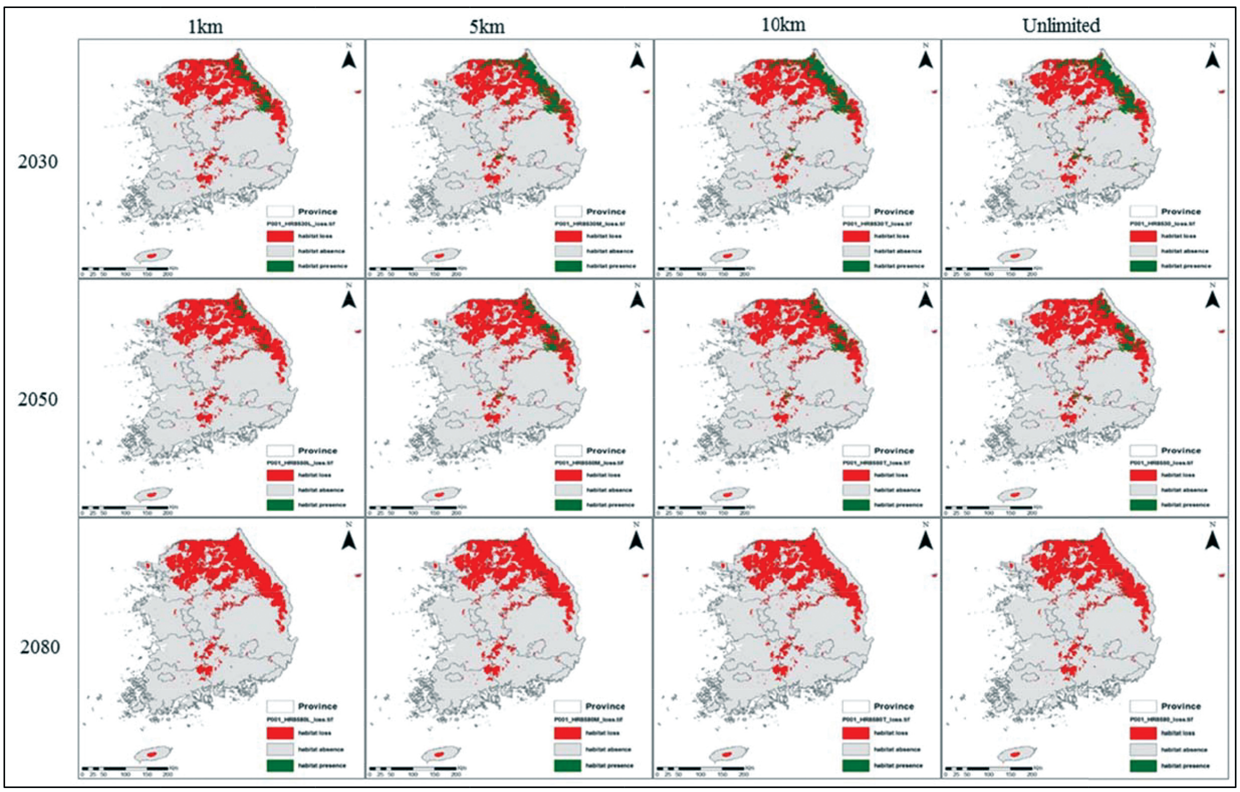

Fig. 5. Potential dispersal of *P. obovata* under climate change scenario RCP 8.5. The black lines on the map show the 17 provinces of Korea. The red, green, and gray colors on the maps indicate habitat loss, habitat presence, and habitat absence, respectively.

Table 4. Area (km^2) of climatically suitable habitat of *Paeonia obovata* in South Korea

Scenario	Year	1km/year	5km/year	10km/year	Unlimited
RCP4.5	2030	3574	5234	5464	5879
	2050	2649	4231	4397	4835
	2080	56	610	961	1057
RCP8.5	2030	2518	4683	4949	5376
	2050	1054	2208	2325	2529
	2080	43	191	211	229

responding changes. The temperature increases under RCP 4.5 and RCP 8.5 may exceed the suitable temperature range required for plant germination and growth (Hatfield and Prueger 2015). In this study, temperature-related variables, such as annual mean temperature and isothermality, accounted forthe first and second highest proportions of the model, indicating negative impacts on biological activity. Thus, the climatically suitable area of *P. obovata* could be reduced in the future.

P. obovata is a peony flower that blooms in the spring, starts flowering during the summer and sheds leaves and enters dormancy in late autumn (Halevy *et al.,* 2005). Ending bud dormancy requires exposure to a prolonged period of chilling, similar to the process for many deciduous trees and geophytes (Barzilay *et al.,* 2002; Rhie *et al.,* 2012; Yeo *et al.,* 2012). High temperatures in winter cannot sufficiently chill the dormant bud to break bud dormancy, and in summer, increased temperatures reduce flower formation in the crown's buds, promote flower abortion, and cause immature seed shed (Evans *et al.,* 1990; Halevy *et al.,* 2005).

Globally, *Paeonia* spp. are native to cool temperate climates and are often found at high latitudes and high altitudes, particularly on cliffs in rocky and inhospitable terrain (Halevy *et al.,* 2005; Page 2005). Similar to other countries, in South Korea, highly suitable habitat for *P. obovata* has been predicted in high latitudes (above 37°) and high altitudes, particularly in the northern and northeastern regions of the country (Seoul Province, Incheon Province, Gangwon Province, and Gyeonggi Province). These regions consist of many high mountains (above 721 m ASL), such as Seoraksan, Odaesan, Chiaksan, Taebaeksan, and Sobaeksan. We estimated the potential habitat of *P. obovata* in both the lowlands and high altitudes in the northern and northeastern regions. However, in the central and southern regions (e.g., Chungcheongbuk Province, Chungcheongnam Province, Jeollanam Province, Jeollabuk Province, Gyeongsangnam Province and Jeju Province), suitable habitat was predicted mostly in the high mountains, e.g., Juwangsan, Deogyusan, Jirisan, and Hallasan, and was estimated to cover 4,625 km^2. These results revealed that *P. obovata* could be a cold-adapted species in high altitudes and high latitudes, similar to subalpine species (Evans *et al.,* 1990; Koo *et al.,* 2015; Adhikari *et al.,* 2018).

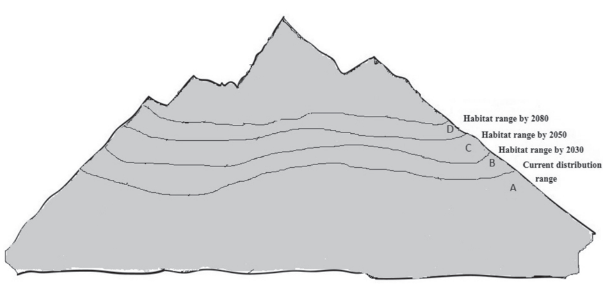

Fig. 6. Diagrammatic sketch of the mountain. A, indicates the habitat range of *P.obovata* under current climate conditions, and B, C, and D indicate the habitat range by 2030, 2050, and 2080, respectively.

The survival of plant populations in different landscapes is strongly dependent on their dispersal potential (Soons and Ozinga, 2005). In nature, plant dispersal is generally achieved via seeds, and seed dispersal occurs through hydrochory (by water), anemochory (dispersal by wind), epizoochory (by adhesion to an animal's body), endozoochory (by animals via feeding) or anthropochory (by humans) (Vittoz and Engler 2007; Poschlod *et al.,* 2013). The seed dispersal of *P. obovata* in South Korea is mainly reported to occur via wild herbivores, e.g., roe deer (*Capreolus pygargus*) and water deer (*Hydropotes inermisargyropus*) (Kim *et al.,* 2016). The mode of seed dispersal determines how far a species can potentially exist in the wild. However, different kinds of barriers, such as mountains, lakes, seas, and urban areas, limit seed dispersal and propagule production, resulting in a decrease in their distribution area (Engler *et al.,* 2012). In addition to geographical barriers, other parameters, such as initial species distribution, habitat suitability, propagule production potential, long distance dispersal, dispersal steps, and number of environmental changes, are important components for estimating the dispersal of *P. obovata,* as suggested by Engler and Guisan (2009) and Engler *et al.* (2012). In this study, we estimated the potential dispersal of *P. obovata* using the dispersal limitations of 1 km/year, 5 km/year, and 10 km/year and unlimited dispersal under the future climate change scenarios RCP 4.5 and RCP 8.5 for 2030, 2050, and 2080. Our study predicted that there would be no large difference in potential habitat under dispersal limitations of 5 km/year, 10 km/year, and unlimited dispersal.

Global warming will require a considerable range shift rate for plant species to exist under similar climatic conditions (Malcolm *et al.,* 2002). Generally, plant species may shift to higher altitudes and latitudes with changes in climatic conditions (Bertrand *et al.,* 2011; Lenior and Svenning, 2013). However, the trends in the range shifts may differ between widely distributed and narrowly distributed plant species. In comparison to widely distributed plant species, thosespecies with narrow distributions usually have a limited ecological adaptation capacity and weaker resistance to climate change (Hu *et al.,* 2015). Many studies have reported early signs of plant migration towards higher elevations under the effects of climate change (Zhang *et al.,* 2001; Leng *et al.,* 2008; Czortek *et al.,* 2018; Wang *et al.*, 2019). *P. obovata*has a narrow distribution range in South Korea and occurs only on high mountains and at high latitudes. Under future climate change conditions, we assume ashifting of its range to higher elevations and higher latitudes than its current distribution ranges. Although it is not experimentally verified, we designed a figure to explain the potential range shift of *P. obovata* by 2030, 2050, and 2080 (Figure 6).

As shown in Figure 6, mountains are steep and have less surface area and increase in altitude, resulting in a reductionin hospitable terrain for biodiversity. In this study, we estimated that the potential habitat of *P. obovata* will decrease by 2030, 2050, and 2080, and the rate of habitat reduction would be at a maximum by 2030 and is estimated to decline by 70.63% and 73.04% under RCP 4.5 and RCP 8.5, respectively. The integrated impacts of climate change on biological activity and decreases in the land surface for the growing plant population could be the possible reasons for the sharp decline in the potential habitat of *P. obovata* by 2030.

In addition to climate change, several anthropogenic factors, such as land use and land cover change, road construction, overexploitation for medicinal and cosmetic purposes, and human-caused invasions, may decrease the habitat area of *P. obovata*. Additionally, over grazing and browsing of wild herbivores such as the long tailed ghoral (*Naemorhedus caudatus*), roe deer, and water deer during germination and the growing season can decrease the plant population of (Goetsh and Wigg, 2011; Adhikari *et al.,* 2016) *P. obovata.* The results of this study may suggest that *P. obovata* has a high degree of vulnerability to climate change effects; nonetheless, human-induced activities andloss of suitable habitat for *P. obovata* will be more than expected. Therefore, further studies are required to quantify and qualify future human-caused impacts on the sustainability of *P. obovata.*

Although this study provided valuable information about the potential dispersal of *P. obovata* under different dispersal limitations, our model was based on only bioclimatic variables, without the use of land cover change, biotic interactions including competition and facilitation, and biological invasions as suggested by Martin *et al.* (2013) and Ahmad *et al.* (2018). This study is a part of ongoing research; in our next study, we will consider using other nonclimatic variables, such as land cover change, roads, biological invasions, and data on human utilization, to obtain more accurate estimations in the near future.

Conclusion

We predicted the potential dispersal of *P. obovata* under current and future climate change conditions using MaxEnt and MigClim models. Temperature-related variables such as annual mean temperature (Bio1), mean diurnal temperature range (Bio2), and isothermality (Bio3) were the three most important climate factors determining the dispersal of *P. obovata*. As a high altitude and latitude plant species and as a species sensitive to high temperature, the habitat of *P. obovata* might be significantly reduced by 2080 under the predicted climate change scenarios. This study is crucial to understanding the spatiotemporal dynamics of *P. obovata* under climate change conditions. Furthermore, this work will be crucial in identifying current and future distribution habitats, developing management strategies such as *insitu* and *exsitu* conservation, harvesting sustainably, and implementing artificial seed dispersal to protect this species in the wild for its ecological and economic benefits. Based on our study, we recommend conducting the necessary conservation activities in natural habitats of P. *obovata,* particularly focusing on the northern, northern east, and southern regions of the country, including Seoraksan, Odaesan, Chiaksan, Taebaeksan, Juwangsan, Deogyusan, Jirisan, and Hallasan.

Conflict of interest

The authors declare that they have no competing interests.

Funding

This study was supported by Korea Environment

Industry and Technology Institute (KEITI) through the "Climate Change Response Technology Project", funded by Korea Ministry of Environment (2014001310009). Therefore, authors are grateful to the project for providing the research fund.

Contribution

# Ja-Young Jeon and Pradeep Adhikari contributed equally to this manuscript.

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